STUDY OF CAPACITOR-EXCITED INDUCTION GENERATORS; PARALLEL OPERATION AND TRANSIENT LOADING

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by

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Submitted in Partial Fulfillment

of the Requirements for the

Degree of Naval Engineer

From the

Massachusetts Institute of Technology

1951

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Submitted for the degree of Naval Engineer in the Department of Naval Architecture and Marine Engineering on 18 May 1951.

I. ABSTRACT

The induction machine as an independent generator of a-c power has been ignored in favor of the synchronous machine. As of this date, little information on the steady state characteristics of the induction generator appears in the literature; information on paralleling and on transient behavior could not be found.

The object of this thesis is an investigation into the characteristics of the shunt capacitor-excited induction generator both in steady state and during transients with an eye toward the possibilities of its use in special power plants.

It is revealed that the induction generator -

(a) in conjunction with static condensers can generate and deliver rated power with a pure sine wave voltage and an efficiency comparable to that of a synchronous generator.

(b) is an "asynchronous" machine, but its generated frequency is controllable by automatic regulation.

(c) is especially desirable and adaptable when specifications call for high rotor speeds for high frequency power supply.

The paralleling of two induction generators is an operation of extreme simplicity requiring no special equipment such as synchroscopes and no special skill of the operator.

Under fault conditions, all voltages and current transients are substantially over after, at most, six cycles. A short circuit merely drains the excitation from the induction generator and the voltage quickly collapses. The generator currents are limited to about four times the rated current for the first cycle and less than rated current for the remaining transient. Thus, the nature of the induction generator connections, that is, shunt condensers across the stator terminals of the induction machine, makes for inherent generator safety.

Cambridge, Massachusetts

May 18, 1951

Professor J. S. Newell
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

In accordance with the requirements for the Degree of Naval Engineer, we submit herewith a thesis entitled "Study of Capacitor-Excited Induction Generators; Parallel Operation and Transient Loading".

Respectfully,

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to Professor Alexander Kusko for his advice and encouragement; to Professor Waldo V. Lyons for his helpful suggestions; and to Mr. P. N. Heller for his instruction in oscillography.

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II. INTRODUCTION

It is well known that when an induction motor is driven above synchronous speed it becomes a generator and delivers power to the bus to which it is connected. A common impression appears to exist that in order for an induction machine to operate as a generator it must be connected to a source of a-c power. Such is not the case; an induction machine may operate as an independent source of power, the magnetizing current being supplied by static capacitors.

The fact that such operation is possible has been known for some time[1,2*], but little has been written on this subject until recently. Smaller, lighter, and less expensive capacitors of today make more feasible the use of induction generators for a-c power generators. The use of a squirrel cage rotor in the induction generator offers advantages of (1) ruggedness, (2) low maintenance, (3) higher speed possibilities, and (4) low cost of construction.

No information could be found in the literature on paralleling of induction generators or on the transients that exist in the machine under normal and abnormal operation.

This thesis is an investigation of the characteristics of a shunt capacitor-excited induction generator both in steady state and undergoing transients of (1) voltage build up,

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* Superscripts refer to references as listed in the bibliography, Appendix.

(2) starting an induction motor load, (3) paralleling with another induction generator, and (4) short circuits.

III. PROCEDURE

The procedure used in this thesis was experimental in nature. In steady state the characteristics of an induction generator were observed. Instrumentation was provided to indicate generated voltage and frequency, generator and load currents, load power, and load power factor. The practicability of paralleling two induction generators was investigated. A frequency regulator for a single induction generator was designed and its characteristics measured.

Using an oscillograph, responses of generated voltage, line current, and generator current were recorded for a single generator under the following transients:

(a) No load voltage build up.

(b) Starting an induction motor.

(c) Three phase short circuit.

(d) Single phase short circuit.

(e) Paralleling two generators.

(f) Frequency regulation following a step load.

The details of the experimental procedure together with a circuit diagram for steady state and paralleling operation testing appear in the Appendix.

IV. RESULTS AND DISCUSSION OF RESULTS

A. Steady State Characteristics

When an induction machine connected to a source of electrical power is driven above synchronous speed, its slip, $\frac{n_s - n}{n_s}$, is negative and the machine acts as a generator delivering electrical power to the source. Moreover, if the machine is connected to a capacitive impedance, the leading current drawn by that impedance will excite the stator winding, and the machine can operate independently as an a-c generator; i.e., it is no longer required that the machine be connected to a source of electrical power. Assurance that the machine sees a capacitative impedance can be provided by shunt capacitance across the machine terminals.

The no load voltage of an induction generator with capacitor-excitation is determined by the intersection of the saturation curve (no load voltage vs. stator current) and the reactance line for X_c.[4] (See Fig. I.) If X_c becomes too large (i.e., if the excitation capacitance is too small) the machine cannot hold a voltage. The similarity of determining no load voltage in a d-c machine is to be noted.

A method for calculating the steady state performance of the induction generator has been developed by Dr. J.B. Friauf, of the Bureau of Ships, (United States) Navy Department[7].

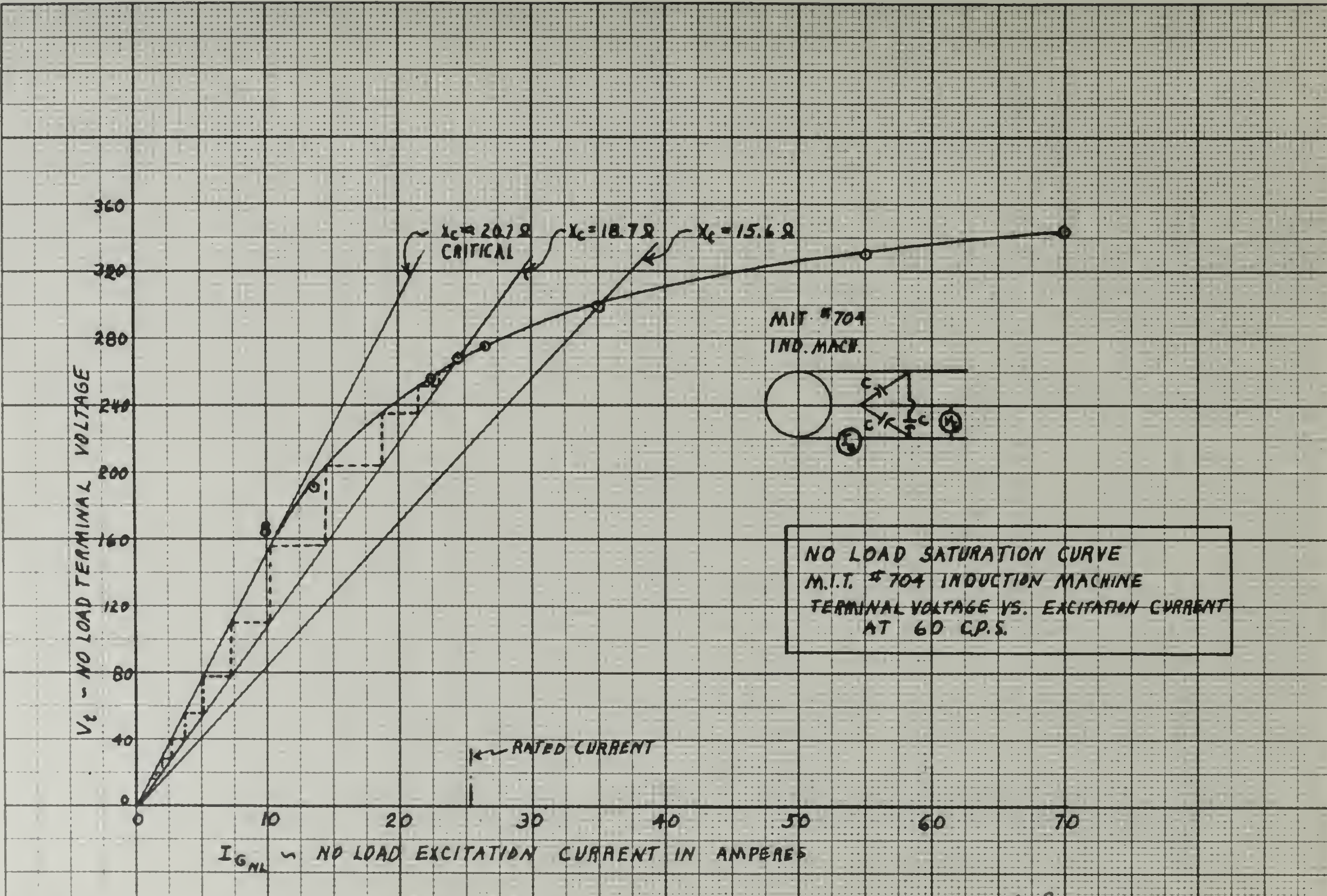

FIG. I

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ESTES & HUSSONG 4-19-51

This method, which has been verified experimentally[8], is based on the equivalent circuit of the induction machine. It shows that the induction generator with shunt capacitor-excitation can deliver power to an increasing load until (referring to the equivalent circuit, Fig. II) the vector sum of the admittance of the stator and load branch, Y_1, plus the admittance of the rotor branch, Y_2, becomes less than the required magnetizing susceptance, Y_{m_c}. At this point the generator loses excitation and the voltage collapses. Further verification of this calculation method is seen in Fig. III which is a composite curve of the steady state characteristics of the two generators used in the experimental work.

In Fig. III the load curves for the two generators have been rationalized and placed on a per unit basis so that with unity power factor, 1.0 per unit load current gives 1.0 per unit voltage. The raw data from which the curves in Fig. III are plotted is tabulated in the Appendix and is plotted in Fig. A-II*. Also a schematic diagram of the circuit used in the steady state and parallel operation testing is shown in Fig. A-I.

Referring again to Fig. III, it will be noted that with unity power factor the voltage holds up under much greater

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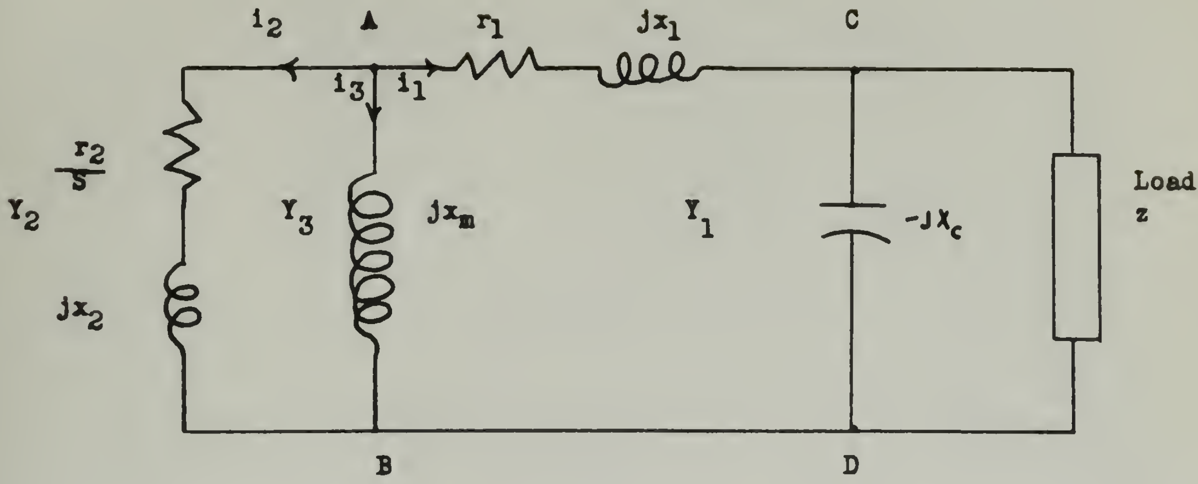
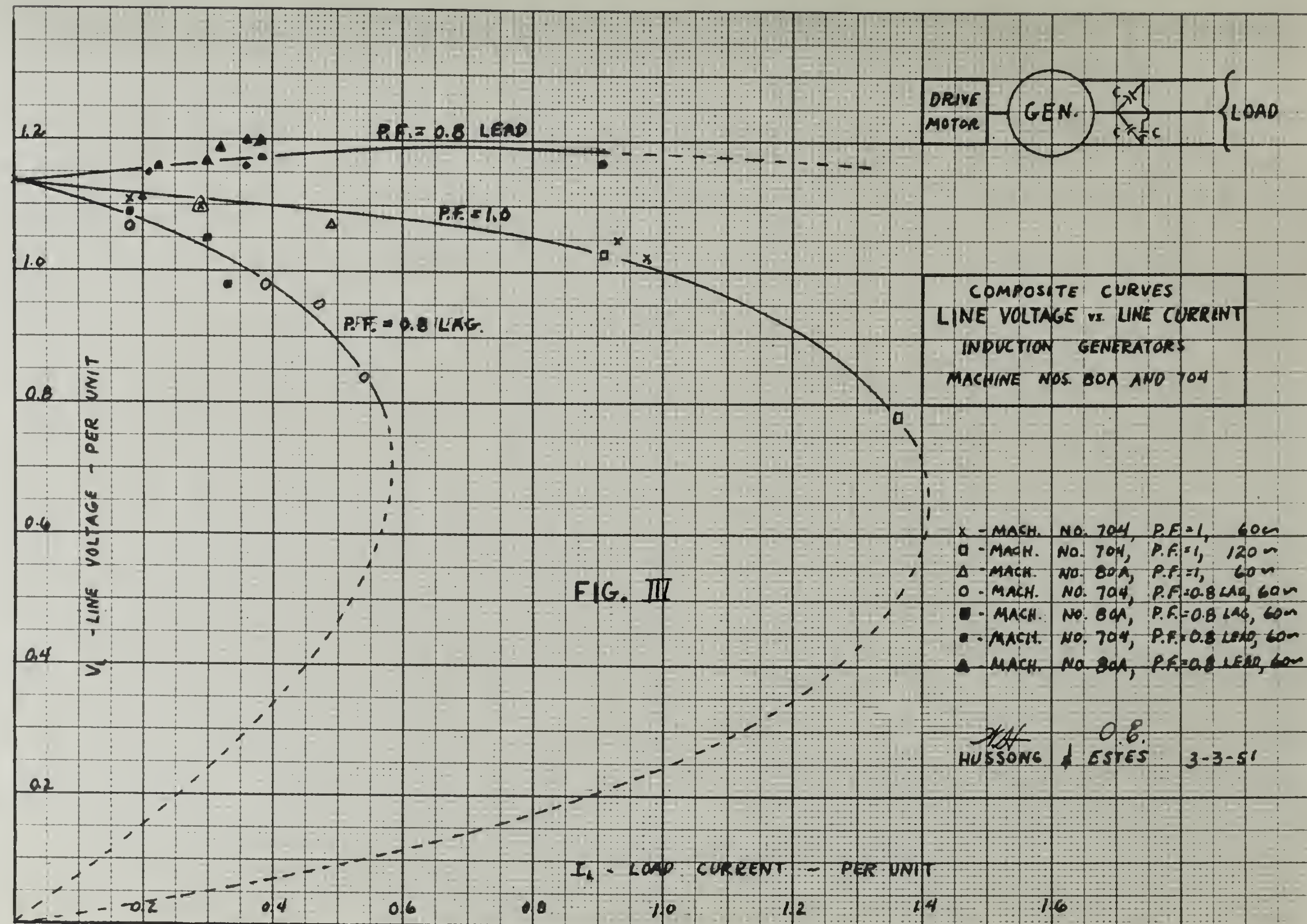
* Fig. A-I and Fig. A-II are in the Appendix.

EQUIVALENT CIRCUIT



r_1 - stator resistance
r_2 - rotor resistance for 1:1 ratio
x_1 - stator reactance
x_2 - rotor reactance for 1:1 ratio at synchronous frequency
s - slip
x_m - magnetizing reactance
x_c - reactance of capacitor for excitation
z - load impedance
Y_1 - admittance of the complete circuit to the right of points A and B
Y_2 - admittance of the rotor circuit to the left of points A and B
Y_3 - admittance of the magnetizing reactance connected directly between points A and B
i_1, i_2, i_3 - currents as indicated on the figure

Fig. II



DRIVE MOTOR
GEN.
C
C
C
LOAD
P.F. = 0.8 LEAD
P.F. = 1.0
P.F. = 0.8 LAG.
COMPOSITE CURVES
LINE VOLTAGE vs. LINE CURRENT
INDUCTION GENERATORS
MACHINE NOS. 80A AND 704
x - MACH. NO. 704, P.F.=1, 60~
□ - MACH. NO. 704, P.F.=1, 120~
Δ - MACH. NO. 80A, P.F.=1, 60~
O - MACH. NO. 704, P.F.=0.8 LAG, 60~
■ - MACH. NO. 80A, P.F.=0.8 LAG, 60~
• - MACH. NO. 704, P.F.=0.8 LEAD, 60~
▲ - MACH. NO. 80A, P.F.=0.8 LEAD, 60~
HUSSONG & ESTES 3-3-51
V_L - LINE VOLTAGE - PER UNIT
I_L - LOAD CURRENT - PER UNIT
1.2
1.0
0.8
0.6
0.4
0.2
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6

FIG. III

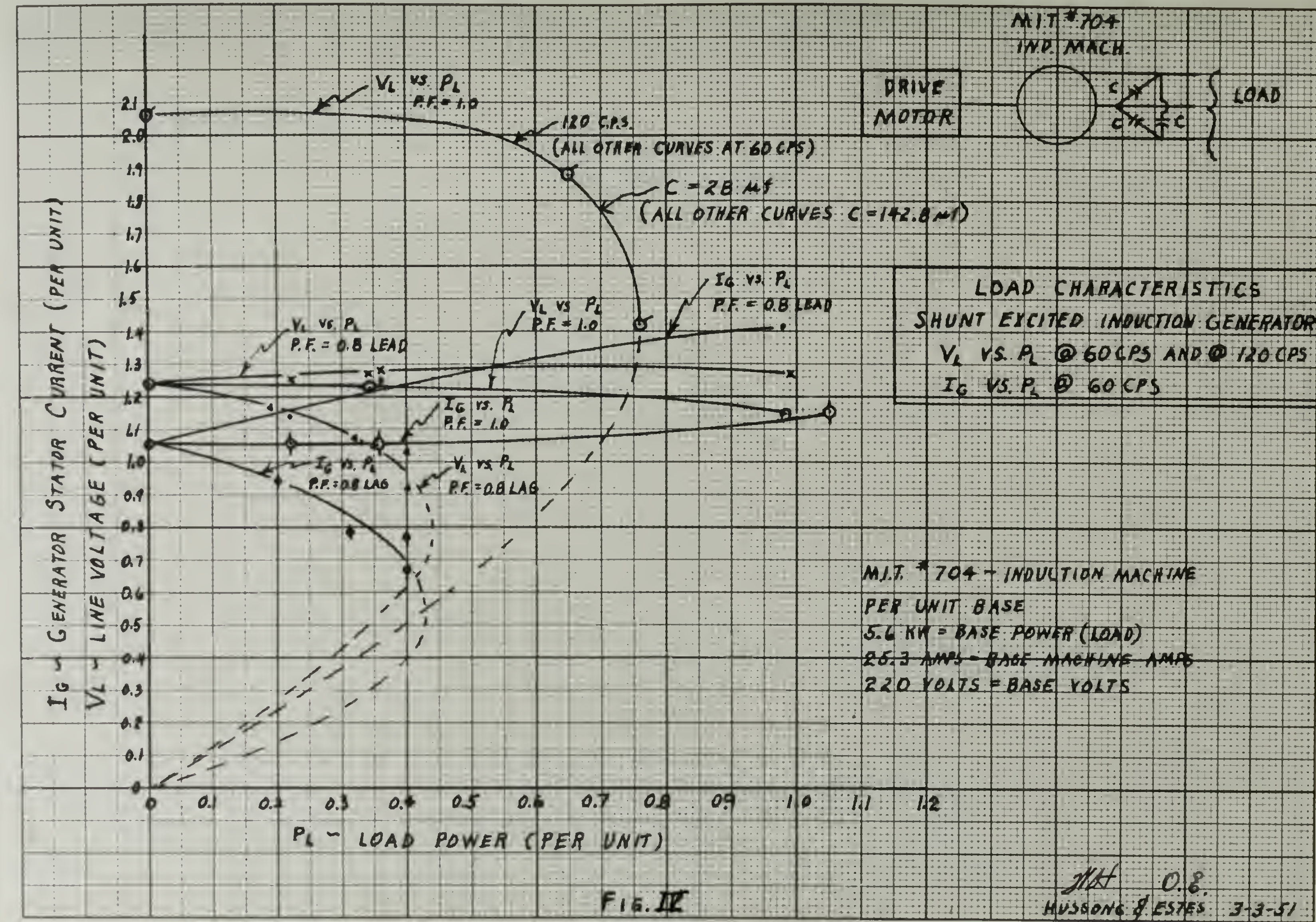
load than with a power factor of 0.8 lagging. A leading power factor load will increase the excitation, and thus the voltage, until limited by saturation. However, the armature resistance will at higher values of load current decrease the line voltage. Actually this phenomena could not be fully tested because of the heavy currents imposed on the machine. It will be observed in Fig. III that the last experimental point on the leading power factor curve is at I_L = 0.9 per unit. At this point the generator is carrying the vector sum of the capacitor current plus the load current, about 1.42 per unit.

If it is essential that the generator deliver nearly constant voltage over its power range, a solution to the problem is variation of the excitation reactance to provide more or less (depending on power factor) capacitance at higher loads. This might be done by using a voltage error measuring means which would compare line voltage to a reference and deliver an error voltage as an output. This error voltage in turn might then be used to adjust the excitation capacitance to bring the generated voltage to the reference level. However, the time lag in such a control system must be small compared to the time of voltage build up (to be discussed later) of the induction generator because if the load is suddenly disconnected and the excitation capacitance is held high, dangerously large voltages and excitation currents may result.

IV. RESULTS AND DISCUSSION OF RESULTS (cont.)

If the feature of voltage collapse under heavy loads is unacceptable, compound excitation may be used. Compound excitation provides a capacitor in series with tho load in addition to the shunt capacitor. It is readily seen that under this arrangement the machine cannot lose excitation even when the load is a dead short, for such a condition merely provides another capacitor in parallel with the shunt capacitor. There are, unfortunately, conflicting requirements on the series capacitor. It must be very large so that no substantial voltage drop is lost in it before the voltage is delivered to the load. However, if a short occurs across the load, a very large series capacitor will then draw dangerously large currents and may build up excessive voltages in the machine.

In Fig. IV, load characteristics of machine No. 704 have been plotted on a per unit basis with rated values of power, current, and voltage chosen as bases. These curves in addition to showing the drop-off of voltage at higher powers indicate the relationship of generator stator current, I_G, with load. Since $\overline{I}_G=\overline{I}_C+\overline{I}_L$, the case of the lagging power factor load shows generator current rapidly dropping off with increasing load until the excitation is lost. With leading power factor the generator current shows an increase with increasing load. With unity power factor the generator current increases only slightly with load.


M.I.T. # 704
IND. MACH.
DRIVE MOTOR
C
C
C
LOAD
LOAD CHARACTERISTICS
SHUNT EXCITED INDUCTION GENERATOR
V_L VS. P_L @ 60 CPS AND @ 120 CPS
I_G VS. P_L @ 60 CPS
V_L vs. P_L P.F. = 1.0
120 C.P.S. (ALL OTHER CURVES AT 60 CPS)
C = 28 μf (ALL OTHER CURVES C = 142.8 μf)
I_G vs. P_L P.F. = 0.8 LEAD
V_L vs P_L P.F. = 1.0
V_L vs. P_L P.F. = 0.8 LEAD
I_G vs. P_L P.F. = 1.0
I_G vs. P_L P.F. = 0.8 LAG
V_L vs. P_L P.F. = 0.8 LAG
I_G ~ GENERATOR STATOR CURRENT (PER UNIT)
V_L ~ LINE VOLTAGE (PER UNIT)
P_L ~ LOAD POWER (PER UNIT)
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.1
M.I.T. # 704 ~ INDUCTION MACHINE
PER UNIT BASE
5.6 KW = BASE POWER (LOAD)
~~25.3 AMPS = BASE MACHINE AMPS~~
220 VOLTS = BASE VOLTS
O.E.
HUSSONG & ESTES 3-3-51
FIG. IV

Even under no load an induction generator with capacitor-excitation has circulating currents in its stator. This exciting current is equal to the phase voltage divided by the phase excitation reactance. The power required to excite the 3.73 KW machine (6 poles) at no load and rated voltage is 0.29 KW, or 7.7% of rated power. For the 5.6 KW machine the power for no load excitation at rated voltage is 0.54 KW or 9.7% of rated power. This larger machine is a pole changing machine and was operated at a synchronous speed of 900 RPM, or 8 poles. The amount of flux in the air gap is proportional to the number of poles and it is to be expected, therefore, that proportionately smaller power is required to excite the machine with fewer poles. Thus, there is a distinct advantage insofar as excitation losses are concerned in designing the induction generator with fewer poles and the corresponding higher speed.

In regard to efficiency of the induction generator, the 5.6 KW unit (Mach. No. 704 coupled to a 7.5 H.P. d-c drive motor) delivered 4.8 KW to a unity power factor load for 7.1 KW d-c power input to the drive motor. The efficiency of the unit then is 67.5%. If the losses are divided equally between the drive motor and the generator, the efficiency of the induction generator is 83%.

The smaller unit (Mach. No. 80A driven by a 4.5 H.P. d-c drive motor) delivered 2.1 KW to a unity power factor load for 3.67 KW d-c power input. The efficiency of the unit then is

slip measuring devices available. But it is important to note here that the speed of the prime mover of an induction generator (if line frequency is to be held constant) must be adjusted so that the rotor speed minus the slip speed is equal to the synchronous speed.

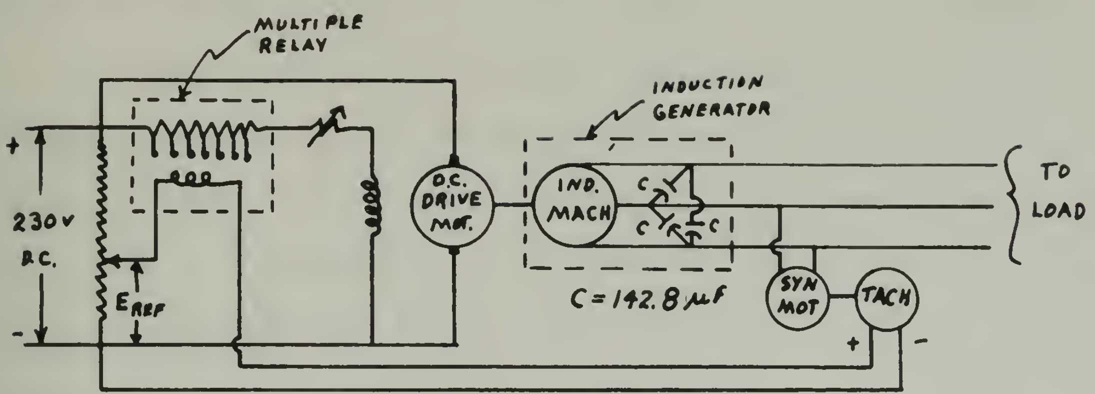
A suggested method of controlling the line frequency is to use a small synchronous motor running off the line. By means of a tachometer connected to the shaft of the synchronous machine, an error voltage proportional to the error in frequency can be fed back to adjust the power input to the prime mover. The circuit diagram for such a system is shown in Fig. V. Since the prime mover in this case was a d-c motor, the error voltage was used to adjust the resistance of the motor field. Measurements of frequency under various loads revealed that up to full load on machine No. 704 the frequency dropped off less than 0.4 cycles per second which corresponds to a frequency error of 0.667 per cent. By the use of more sensitive relays, this error could have been reduced.

B. Transients In Induction Generator Operation

No Load Voltage Build Up

As is the case with a self excited d-c generator, a requirement for initiating voltage build up in a capacitor-excited induction generator is the presence of residual magnetism. In the course of the experimental work the voltage

FREQUENCY REGULATOR



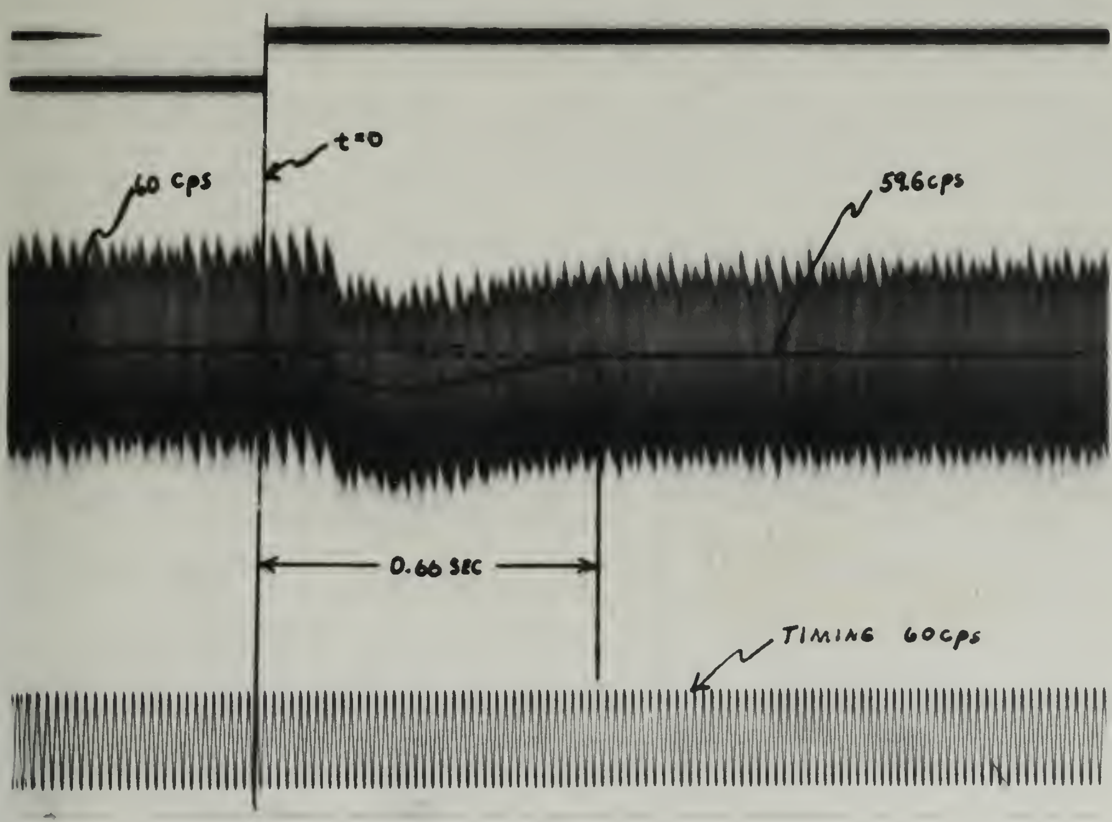


FIG V

was built up several hundred times; and in only one case was it necessary to flash the field using an external source.

In 1935 Bassett and Potter[4] demonstrated the anology of voltage build up in the capacitor-excited induction generator to the voltage build up in a direct current generator. Fig. I shows the no load saturation curve of machine No. 704. This curve shows that there is a critical capacitive reactance above which the generator will not build up. If C=142.8 microfarads, then X_c=18.7 ohms and the generator terminal voltage builds up to 267 volts. If C is increased until X_c= 15.7 ohms the terminal voltage builds up to 300 volts. The dotted lines in this figure are inserted to show qualitatively the rate of voltage build up. It is seen that the rate of build up increases up to point B on the saturation curve and then decreases until the voltage settles down to that determined by X_c.

Fig. VI, which is an oscillogram of voltage build up of machine No. 704, bears out the discussion above. Neglecting the initial transient, which is of short duration and of no consequence, it is seen that the voltage builds up slowly at first. The rate of build up, indicated by the envelope (not shown) of line III increases until B - B is reached. B - B on Fig. VI compares to point B on Fig. I. Beyond B - B, the envelope of line III rises at a diminishing rate until it levels off at the steady state voltage determined by X_c.

NO LOAD VOLTAGE BUILD UP

I - i_{GA} - generator stator current

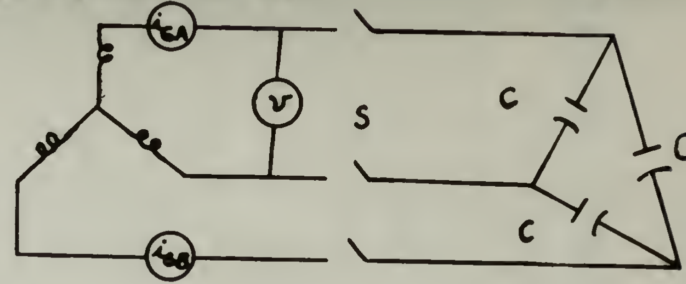
II - i_{GB} - generator stator current

III - v - line voltage

IV - time scale, 60 cps

MIT #704 Ind. Mach.

$C = 142.8 \mu f$



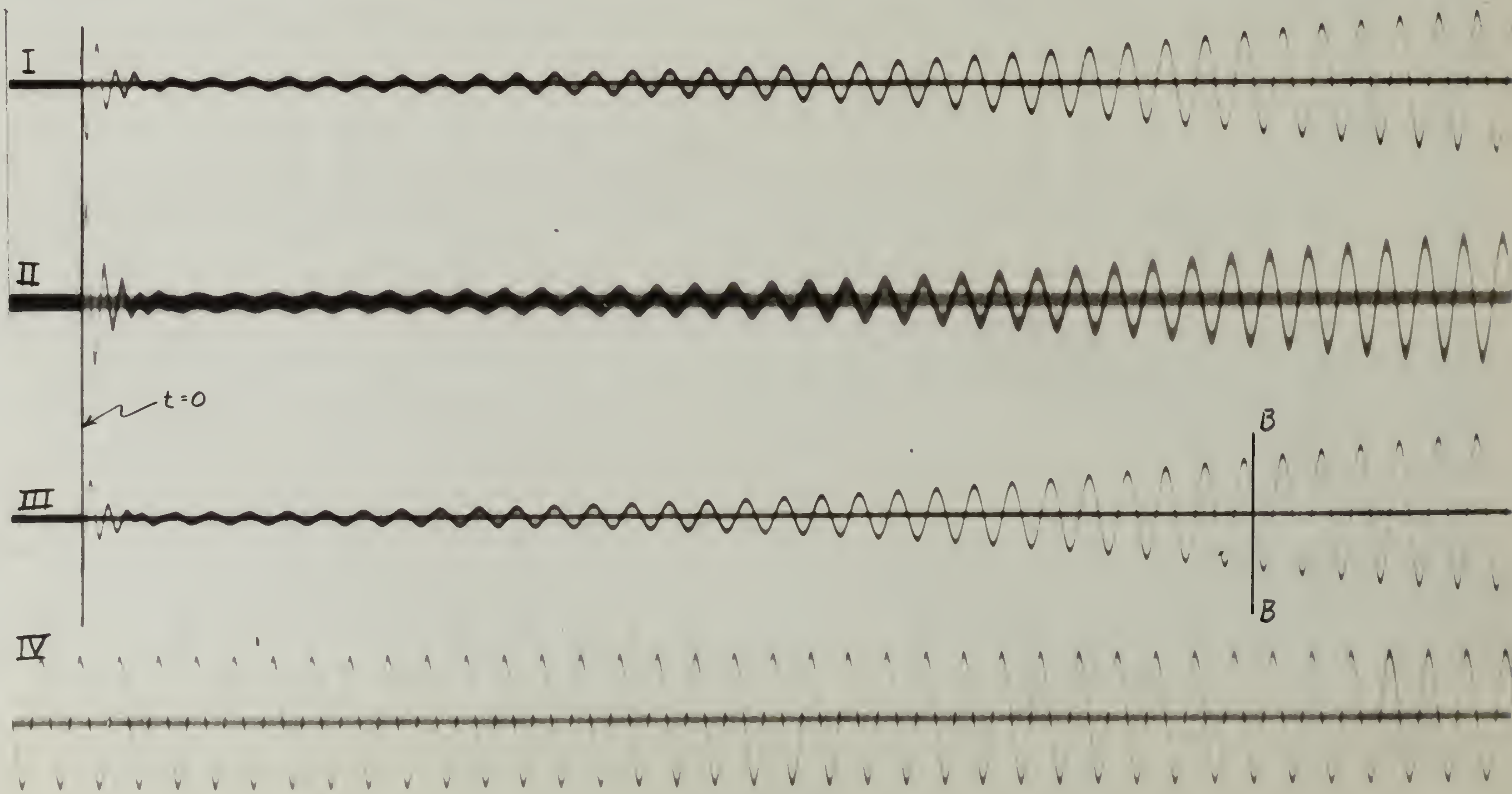


Fig. VI

Starting Induction Motors.

After seeing the induction generator build up to voltage, the next step is to investigate how loading effects the machine. Line I of Fig. VII shows the starting current of a wound rotor induction motor rise to several times running current and decay exponentially to running current value. Slot harmonics due to the presence of the motor's rotor winding slots are evident in this current trace. The generator voltage (line III) and the generator stator current (line II) are seen to dip as the induction motor starts.

The starting transients of a second induction motor, one of squirrel cage rotor construction and of greater rating than the first, is shown in Fig. VIII. Line II shows the starting current to the induction motor. The absence of slot harmonics is noted. Since this motor is rated at double the horsepower rating of the previous motor, and also since an inertia comparable to the rotor inertia itself is attached to this second motor, a greater dip in generator voltage (line III) and a corresponding dip in generator stator current (line I) is to be expected. Lower voltage and current to the machine being started causes its torque to be reduced to a low value, and a relatively long time is needed to accelerate up to final speed, during which time the current decays to running value and the line voltage and stator current build back up almost to the

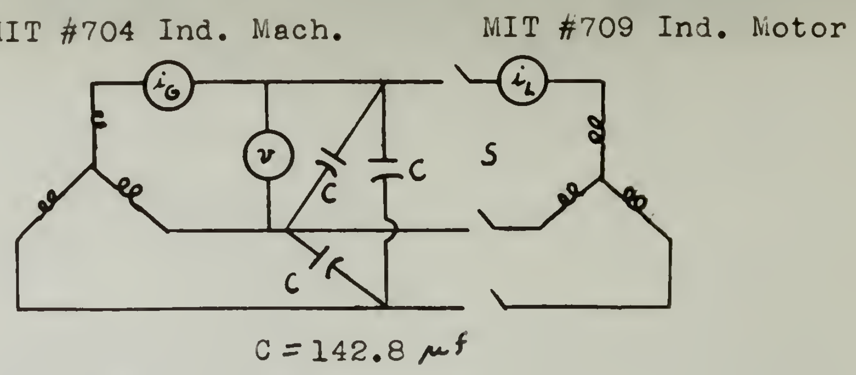
STARTING INDUCTION MOTOR

I - i_L - line current

II - i_G - generator stator current

III - v - line voltage

IV - time scale, 60 cps



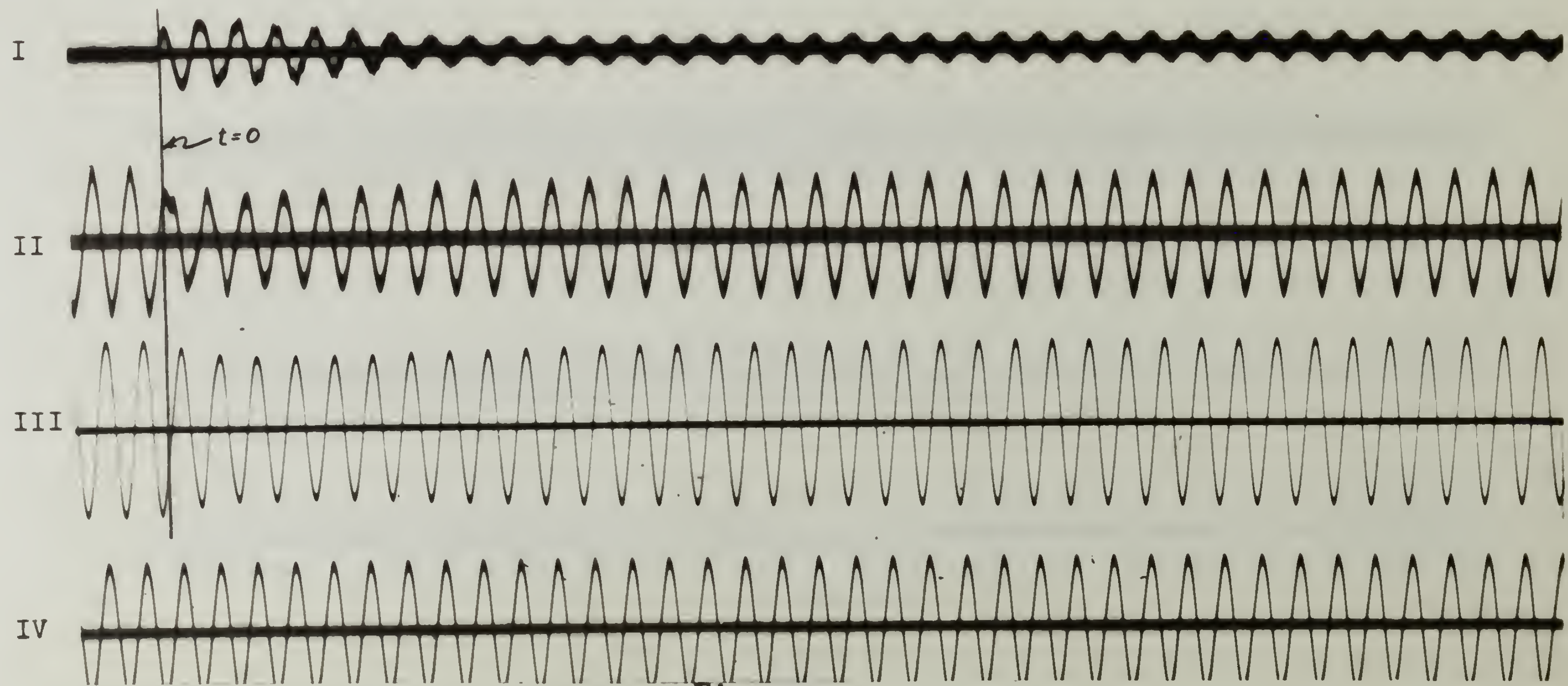


Fig. VII

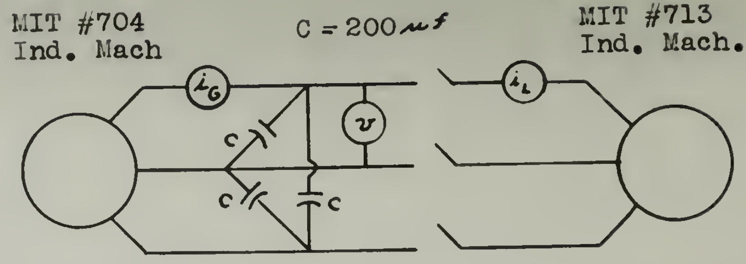
STARTING INDUCTION MOTOR

I - i_G - generator stator current

II - i_L - line current

III - v - line voltage

IV - time scale, 60 cps



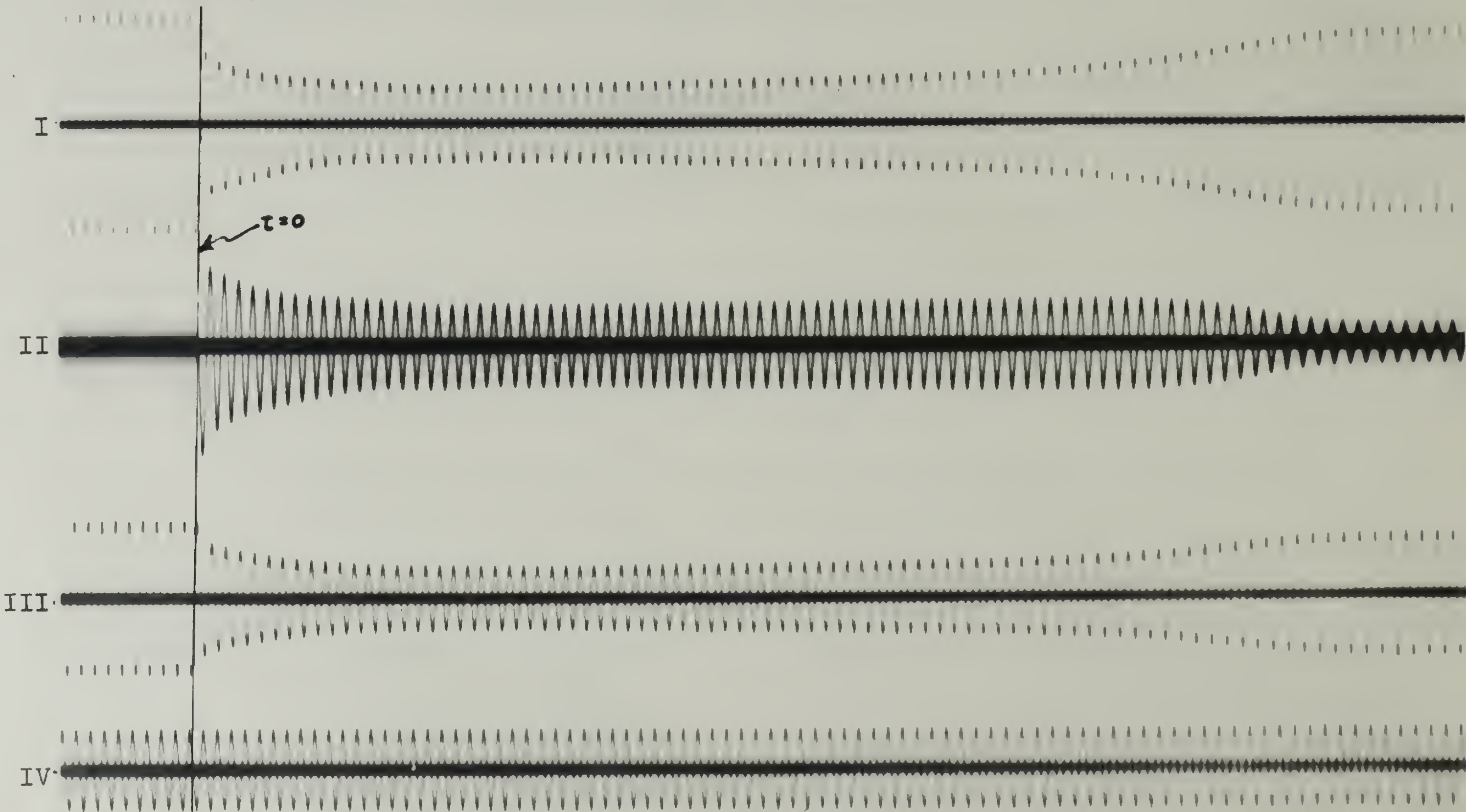


Fig. VIII

original value. The motor (1 H.P.) is about the limiting size that the induction generator (5.6 K.W.) would start. A larger motor load would draw more current from the stator of the generator; the consequent lower voltage and lower line current would produce insufficient starting torque. Thus, the induction generator with shunt capacitor excitation may fail to start a motor load of about one-seventh its own rating. Two possibilities exist to increase the motor load that an induction generator will carry; (1) provide starting compensators for the larger motors, or (2) use compound excitation for the generator.

Three Phase Short Circuit.

For three different conditions of loading, oscillograms were taken to study the induction generator characteristics under a three phase short circuit. Fig. IX shows transients following the short circuit from a small induction motor load. Fig. X shows the transients following the short circuit from rated unity power factor balanced load, and Fig. XI is for the case of unbalanced load consisting of a three phase induction motor load plus an unbalanced single phase lighting load.

In general these three oscillograms indicate that all transients die out in about three cycles. The interesting phenomena is that in no case does the generator have dangerous stator currents. Three to four times rated current for one cycle will not harm an induction machine. The very nature of

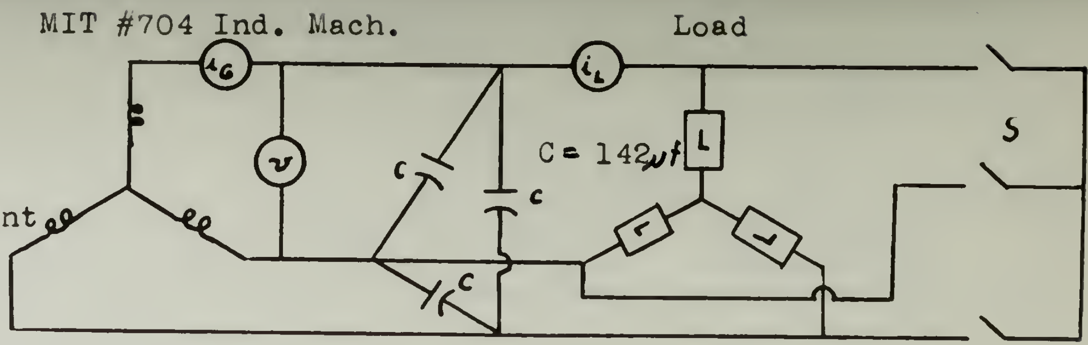
THREE PHASE SHORT CIRCUIT

I - i_L - line current

II - i_G - generator stator current

III - v - line voltage

IV - time scale, 60 cps



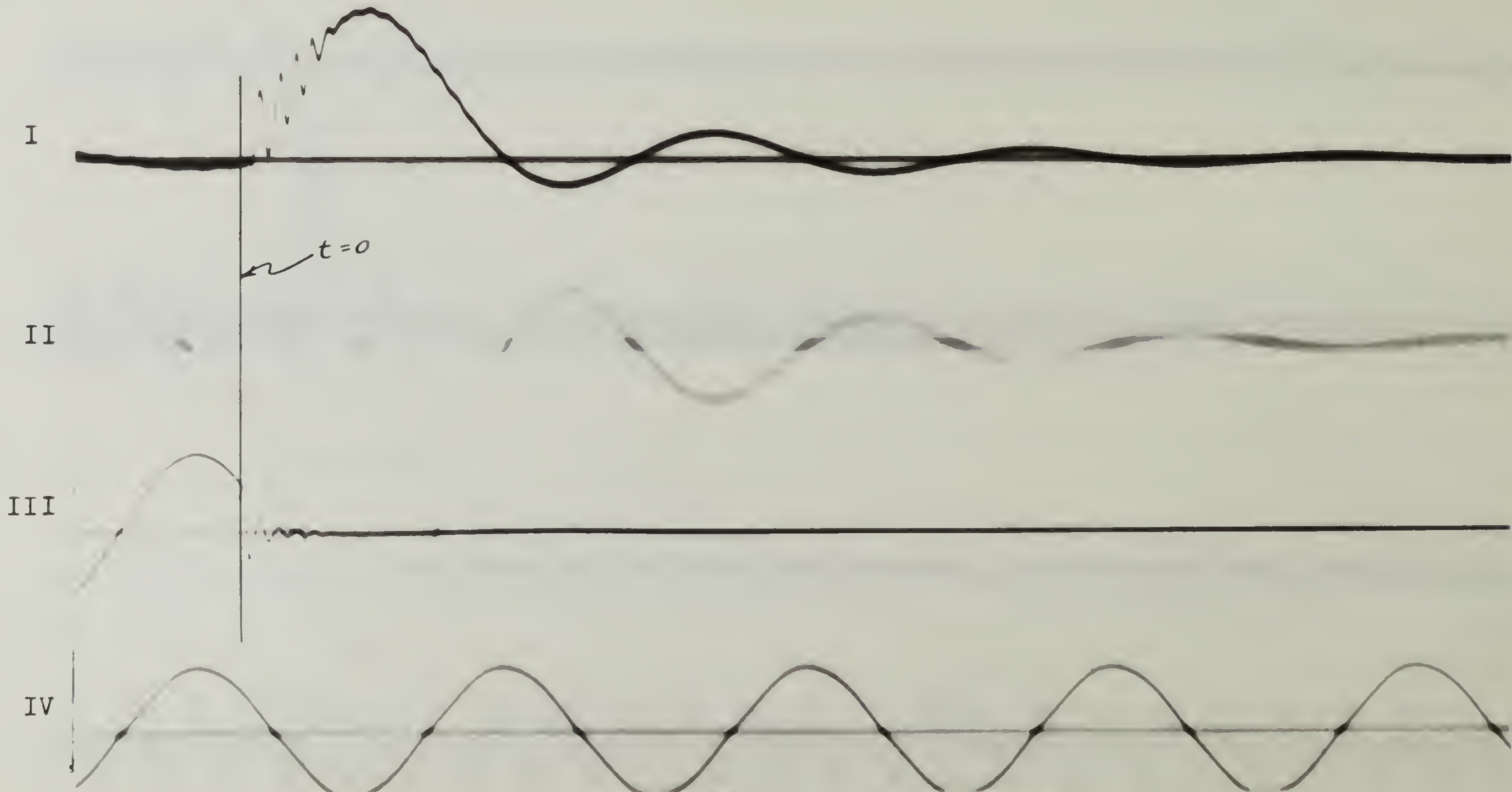


Fig. IX

THREE PHASE SHORT CIRCUIT

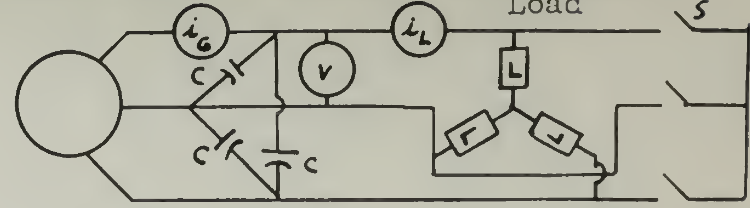
MIT #704
Ind. Mach. $C = 142.8\,\mu f$ Balanced Load

I - i_{GA} - generator stator current

II - i_{LA} - line current

III- v - line voltage

IV- time scale, 60 cps



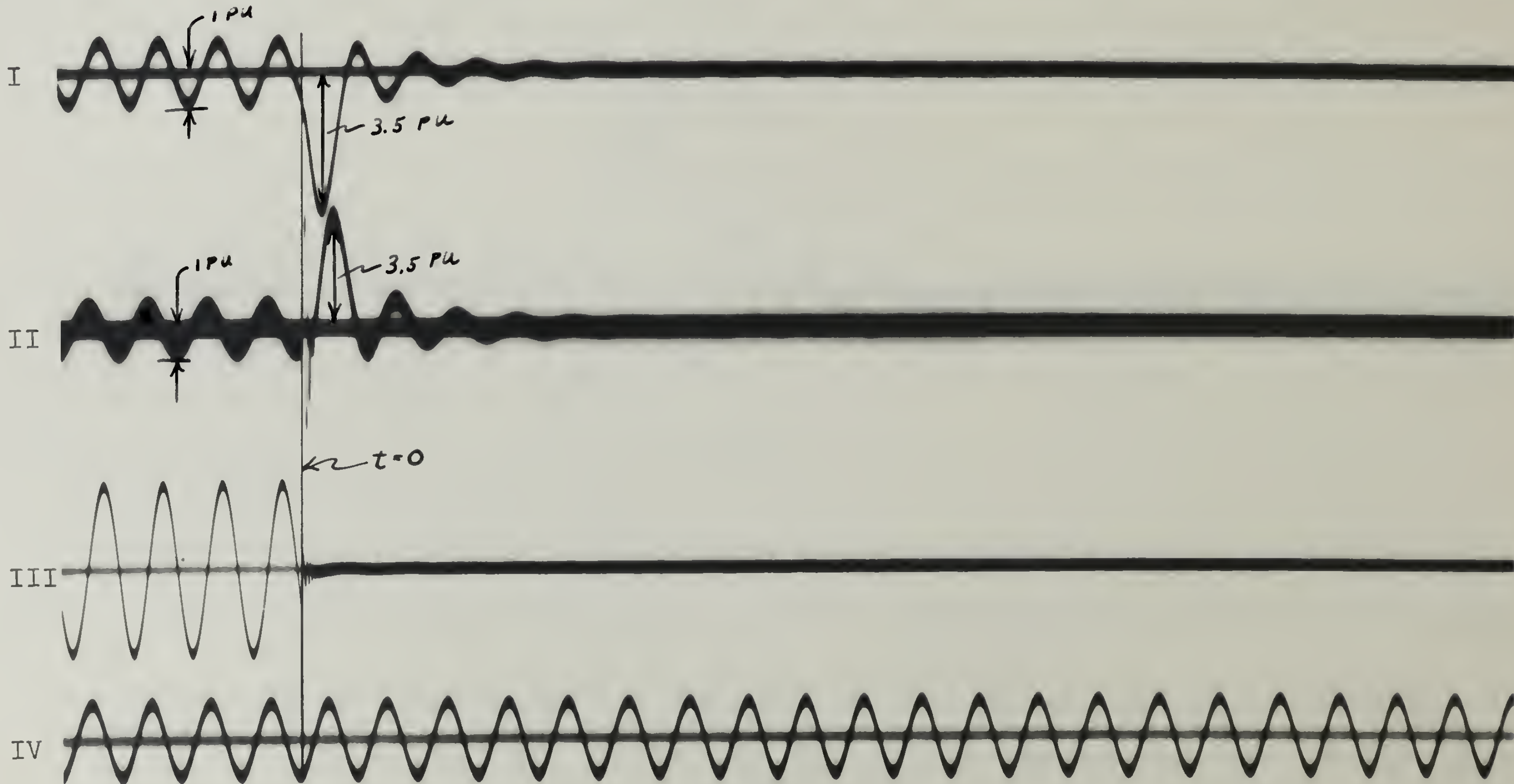


Fig. X

THREE PHASE SHORT CIRCUIT

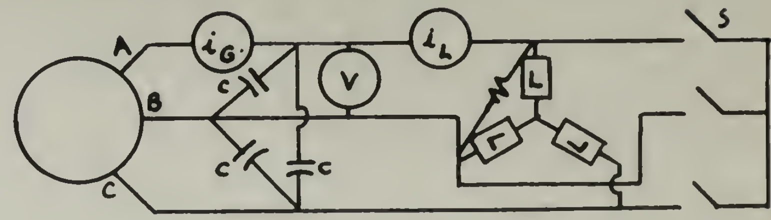
MIT #704
Ind. Mach. $C = 142.8\mu f$ Unbalanced Load

I - i_{GA} - generator stator current

II - i_{LA} - line current

III - v_L - line voltage

IV - time scale, 60 cps



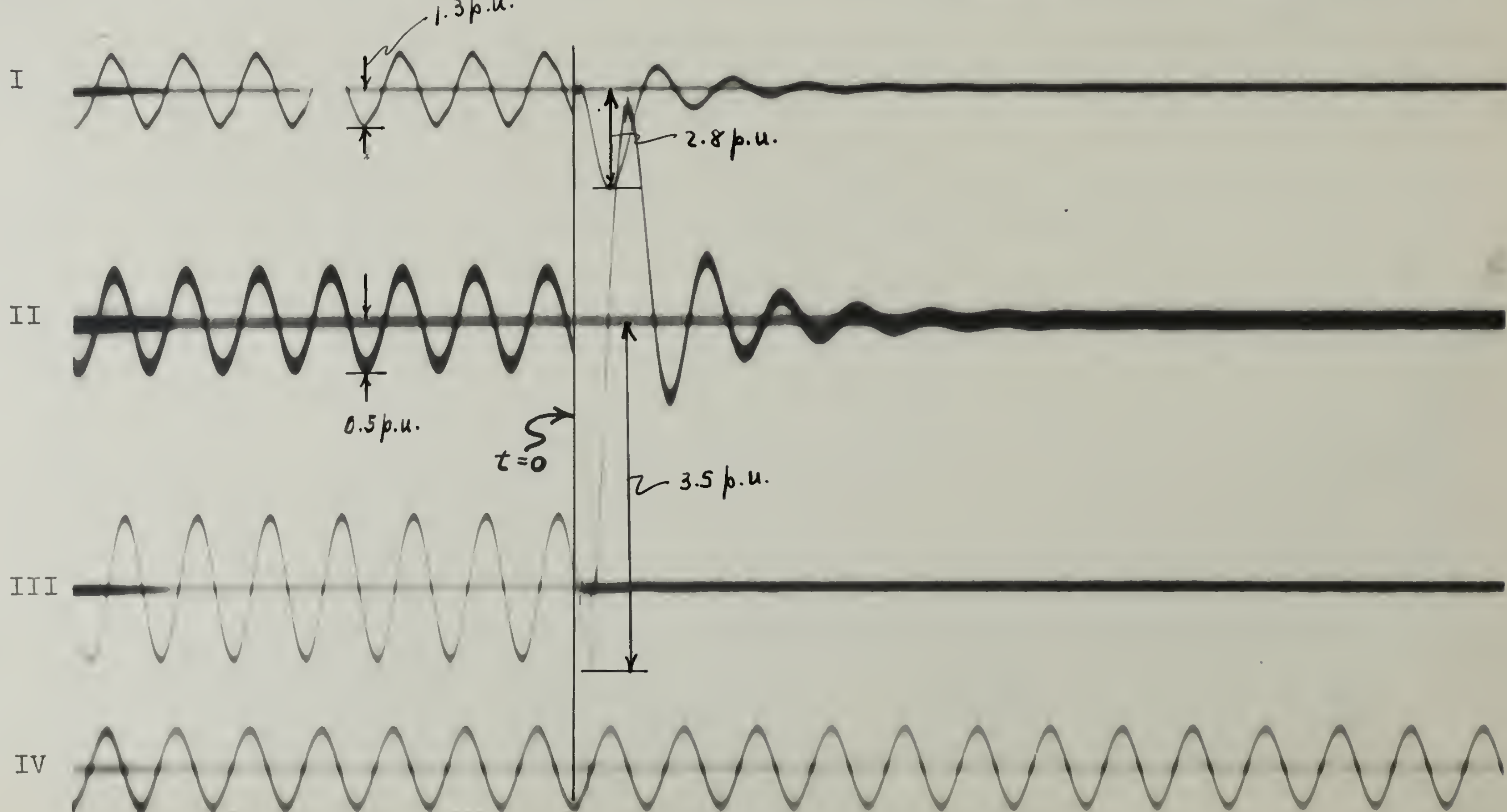


Fig. XI

the shunt capacitor-excited induction generator is to make for machine safety under short circuit. The effect of a short circuit is to draw the charge out of the existing condensers, thus there is no excitation of the generator and the voltage collapses with the decay of the magnetic field in the generator as shown by line III of all three figures.

Referring to Fig. IX in particular, it is interesting to note the exponentially decaying sinusoidal wave of small amplitude and high frequency occuring during the first quarter cycle of the line current trace shown on line I. This decaying sinusoid is most likely a resonance condition set up in the closed path of the exciting condensers (C), the inductance (L), and resistance (R) of lines leading to the short circuiting switch. The frequency of the sinusoid being determined by values of L and C and the rate of decay being determined by R.

Calculation of frequency of sinusoidal exponential decay of high frequency wave component occuring during the first quarter cycle after short circuit:

Converting C_Δ to C_Y; $C_Y = 3\ C_\Delta = 3 \times 143 = 429\ \mu f.$

Length of leads from condensers to shorting switch 15 yards.

Assuming one microhenry of inductance per yard length,

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{1}{LC}} = \frac{1}{2\pi}\sqrt{\frac{10^{12}}{429 \times 15}} = 2000 \text{ cps.}$$

By count of actual curve, f_{res} = 7.5 cycles per quarter cycle of main wave or 7.5 X 4 X 60 $\approx$ 1800 cps.

2000 compared to 1800 is a close order of magnitude check; so the resonance condition assumption is reasonable. Another observation that fits this resonance explanation is the voltage curve (line III) which also has an exponentially decaying sinusoid of the same frequency as the one in the line current.

The same remarks also apply to Fig. X. Since the time scale is compressed in the latter figure the high order exponentially decaying sinusoidal is not clear in the line current (II) but is visible in the voltage wave (III).

Before t = 0 the unbalanced load (Fig. XI) causes an irregular stator current wave (I); however, note the clean sine wave of voltage (III). Thus it is seen that the induction generator is comparable to a transformer; that is, its exciting current varies non sinusoidally to maintain sinusoidal output. This characteristic of giving a pure sine wave has been demonstrated even with salient pole rotors[4]. Except for a slightly longer transient decay, probably due to greater magnetic energy storage, there is little matter in short circuit behavior whether the load on the induction machine is balanced or unbalanced.

Single Phase Short Circuit.

A single phase short circuit is more likely to occur than a three phase short. Fig. XII is a composite of two oscillograms to demonstrate the effect of a single phase short circuit on the induction generator. Having only four elements in the oscillograph used, it was necessary to make two runs to obtain all the desired traces. In this figure lines I - IV are on one oscillogram; lines V - VIII, on a second. The last two inches of the lower traces have been added to make the appearance complete. Other traces which showed this complete die out were used in drawing the curve, and it is, therefore, reasonably correct. Lines I and V are both traces of phase A line current and are seen to match up almost identically. Thus the complete figure might have been obtained by an eight element oscillograph. The traces of line voltage and current before t = 0 give a 60 cps trace for timing reference.

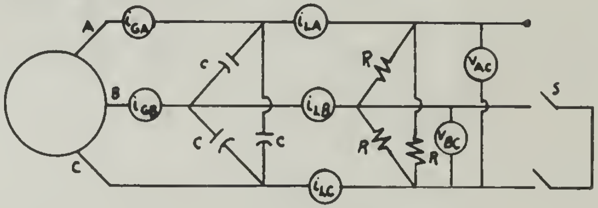
Again, it is found that the induction generator undergoes no serious transients. The highest per unit current in the machine is about three or four as indicated in line III for phase B. Phase C would have been a similar trace displaced by 120 degrees. The worst stator current transient (III) returns to a one per unit value or less after one and a half

SINGLE PHASE SHORT CIRCUIT

MIT #704
Ind. Mach.

C = 142.8 μf

Balanced
Load



I - i_{LA} - line current, A phase (also V)

II - i_{LC} - line current, C phase

III - i_{GB} - generator stator current, B phase

IV - i_{GA} - generator stator current, A phase

V - i_{LA} - line current, A phase (also I)

VI - i_{LB} - line current, B phase

VII - v_{AC} - line voltage

VIII - v_{BC} - line voltage

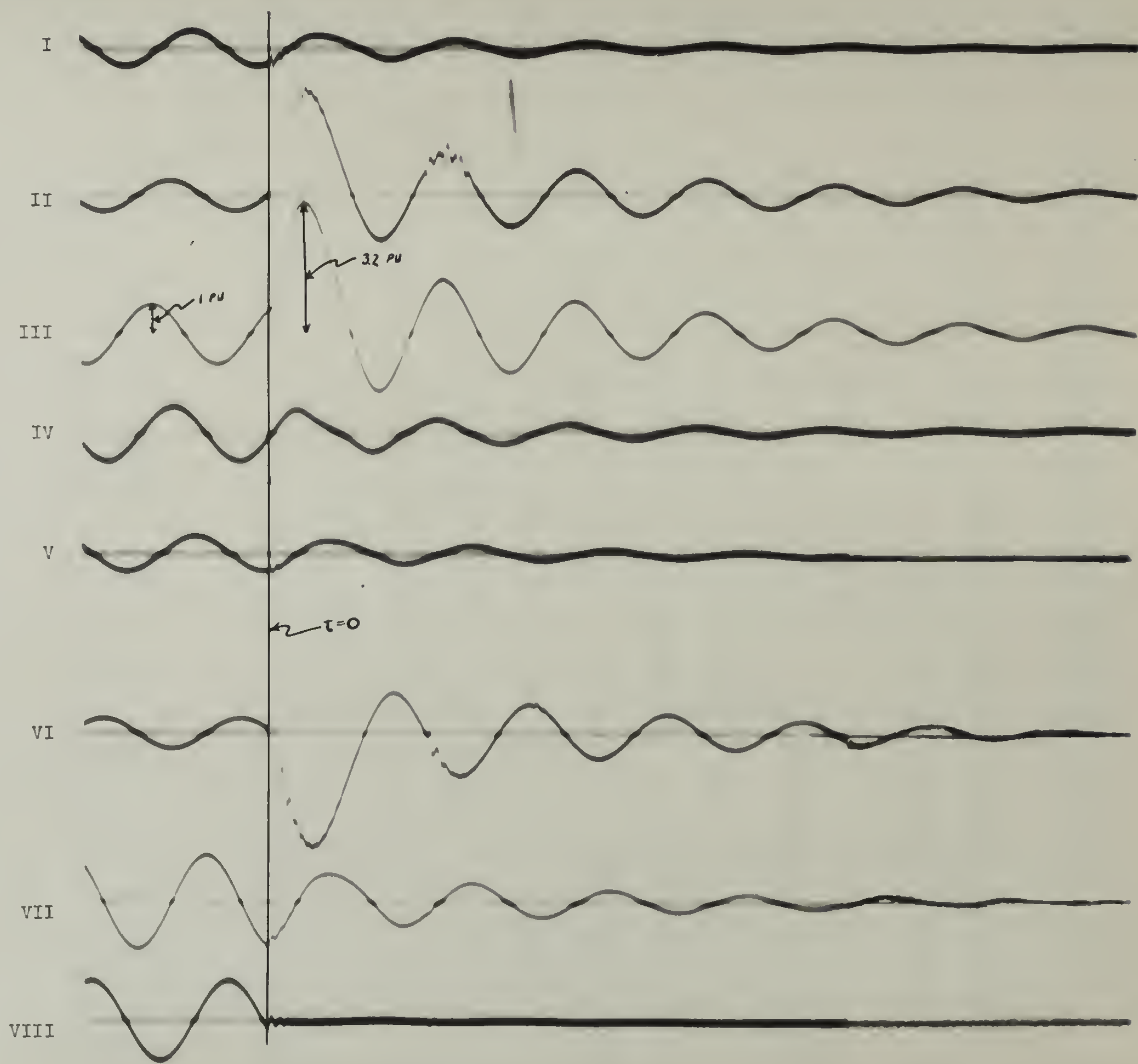


Fig. XII

cycles. The unshorted phase stator current, line IV, never exceeds one per unit and merely decays away as does the unshorted line to line voltage, line VII.

It is interesting to note that the same resonance effect explained by calculation under three phase short circuit exists in the shorted phases of the exciting condensers and lines leading to the shorting switch. Thus the superimposed exponentially decaying sinusoids during the first quarter cycle of lines II, VI, and VIII are probably due to a resonance condition set up by the exciting condensers (C), line inductance (L), and the loop resistance (R). L and C determine the frequency of the sinusoid and R determines the rate of decay.

The decay of voltage takes about six cycles in the single phase short circuit compared to the three cycles of the three phase short circuit. This double time of decay for the single phase short merely shows that a longer time is necessary to dissipate the energy stored in the exciting condensers and in the magnetic field of the machine. The diagram on Fig. XII shows that one excitation capacitor is shorted singly while the others are in series across the short. Since line VIII shows a substantial zero voltage across BC, and since a voltage is indicated across AC in line VII, the voltage across BA must be substantially equal and opposite to the voltage of AC. Thus one exciting condenser can be at zero voltage while

the other two, still having voltage, excite the machine. When the energy of the condensers and magnetic field of the machine have dissipated through the short circuit, the voltage of all phases of the induction generator is zero.

Again it is pointed out that the connections of the induction generator inherently make for safety of the machine under short circuit. The effect of a short is to drain the excitation current from the excitation condensers, which causes voltage collapse. Consequently, the stator currents of the machine are neither large nor of long duration.

Paralleling.

The transients during paralleling are shown in Figs. XIV, XV, and XVI; and are explained in section C, Parallel Operation of Induction Generators. In general the transients in paralleling are of no consequence to the machines.

Frequency Regulation Following A Step Load.

Fig. V shows a circuit diagram of the frequency regulator together with an oscillogram of the frequency response to a step load. It is noted from the oscillogram that the frequency has substantially reached a steady state condition in 0.66 seconds following application of full load at unity power factor. The mean line in the center trace indicates line frequency; the spread of this trace is due to ripple voltage of the d-c tachometer. This regulator was designed

for experimental purposes only. For application to a practical generator, refinement and adaptation would be needed.

C. Parallel Operation Of Induction Generators.

Paralleling may be desirable to meet peak loads or to exchange generators while maintaining continuous service. It is quite possible to parallel shunt capacitor-excited induction generators.

Paralleling Procedure.

The procedure recommended for paralleling is as follows: (1) Bring the incoming machine up to approximately rated speed with no shunt capacitance. (2) At any instant connect the induction machine terminals to the terminals of the induction machine in operation. (3) Adjust the shunt capacitance to obtain the desired line voltage.

The speed of the incoming machine is not too critical. If the incoming machine is running above synchronous speed, the machine will come in as a generator; if running below synchonous speed, the machine will come in as a motor. If the incoming machine's speed is very low or stopped, it acts as a low impedance load on the terminals of the operating machine. This low impedance will draw the exciting current from the operating machine and cause a voltage collapse.

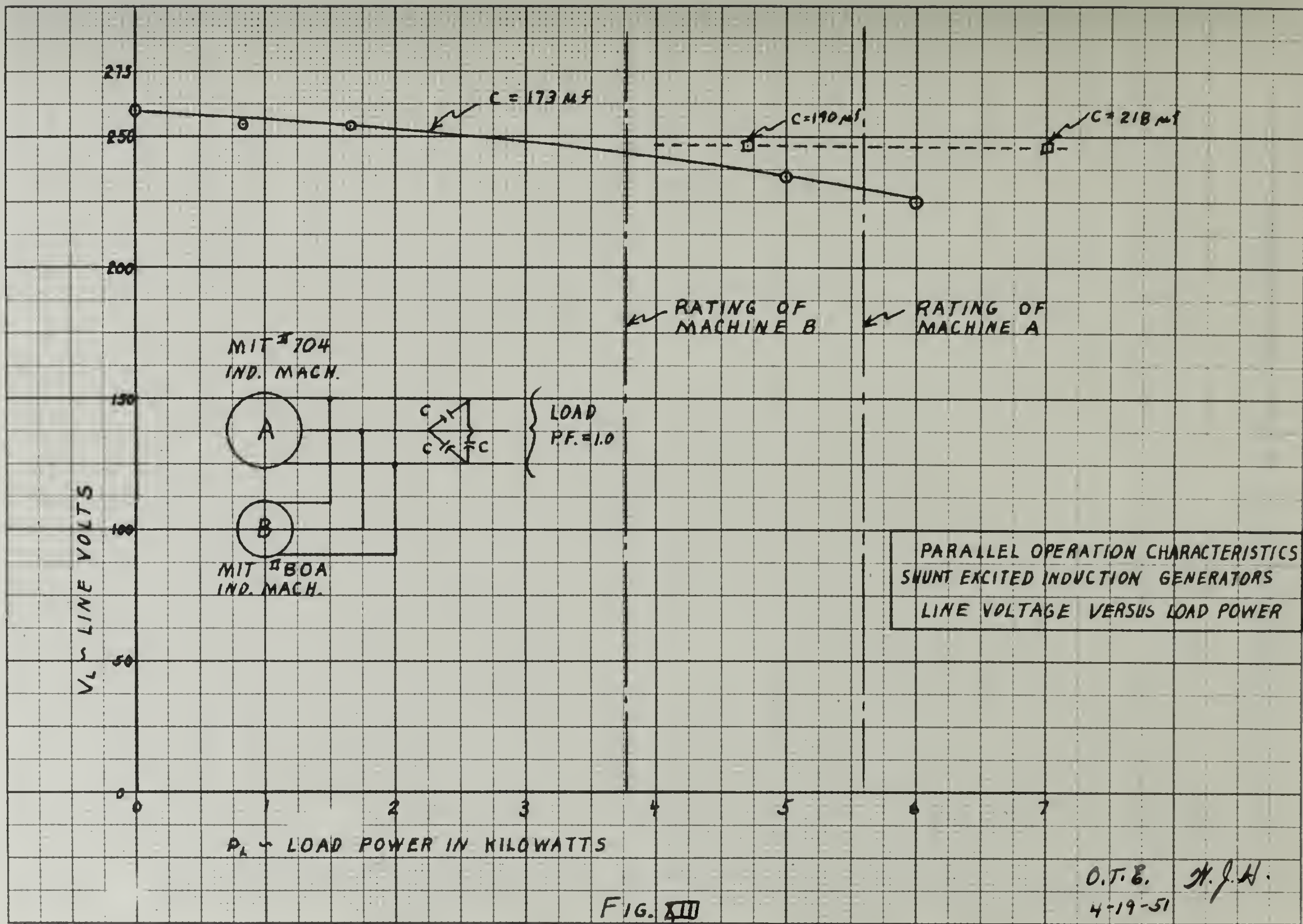
The instant of paralleling is not critical. The transients that follow are of no consequence. The transients are

recorded on oscillograms and are discussed later in this section.

After the instant of paralleling the excitation condensers must excite both machines; thus, the terminal voltage drops. For this reason it is necessary to increase the capacitances to reestablish rated voltage. The capacitances could be increased before or at the instant of paralleling in anticipation of the additional requirement of excitation current.

The above procedure is recommended because of its simplicity. Of course, if the incoming machine were excited by separate condensers, the voltage and the frequency could be adjusted to exactly equal that of the machine in operation; and by the use of synchronizing lamps the proper instant of paralleling is determined in the conventional manner. This method requires more equipment and more care on the part of the operator.

Once the machines are in parallel they act similar to synchronous generators in parallel. Referring to Fig. XIII it is seen that two induction machines in parallel have a drooping voltage characteristic with unity power factor load. This curve compares to the drooping voltage characteristic with unity power factor load of a single generator as shown in Fig. III.



275
250
200
150
100
50
0
0
1
2
3
4
5
6
7
V_L ~ LINE VOLTS
P_L ~ LOAD POWER IN KILOWATTS
C = 173 mf
C=190 mf
C=218 mf
RATING OF MACHINE B
RATING OF MACHINE A
MIT #704 IND. MACH.
MIT #BOA IND. MACH.
A
B
C
C
C
LOAD P.F.=1.0
PARALLEL OPERATION CHARACTERISTICS
SHUNT EXCITED INDUCTION GENERATORS
LINE VOLTAGE VERSUS LOAD POWER
O.T.E.
4-19-51
H.J.H.

FIG. XIII

Induction generators in parallel split the load between themselves in accordance with the power input from their respective prime movers. For example, an increase in load may be met by increasing power from one prime mover. The connected induction generator will be driven at a slightly greater speed (or more negative slip) and the increase in load is supplied by this generator. Alternatively, to meet an increased load both prime movers could be caused to increase power input. Then both induction generators will assume a share of the increase of load. Except for the slip speed changes, which are almost negligible, this action of dividing the load is accomplished in the same manner as is done with synchronous generators.

The dotted curve of Fig. XIII indicates that the line voltage can be maintained at a constant value with varying load by proper adjustment of excitation capacitance. This compares exactly to the field adjustments made in the synchronous generator to maintain constant voltage with load.

Fig. XIV, Fig. XV, and Fig. XVI are samples of the many oscillograms taken to show the transients ensuing after paralleling using the recommended procedure. It is to be noted that in every case the line voltage (line III on the oscillograms) decreases at the instant of paralleling and then slowly builds up as the incoming machine builds up

voltage. (See discussion of Fig. VI on voltage buildup.) This lower voltage helps reduce the transient current which flows in the stator circuit of the incoming machine (line II). The stator current of the machine in operation prior to paralleling is subjected to a less violent transient than the stator current of the incoming machine. In addition to the advantage of comparatively low transient currents it should also be noted that all transients greater than one per unit value last no longer than the first cycle.

If one were to compare the parallel operation of induction generators with synchronous generators the performance characteristics indicated in the preceeding paragraphs would all be listed as advantages of the induction generators.

PARALLELING

I- i_{GA_1} - #1 GEN. STATOR CURRENT

II- i_{GA_2} -#2 GEN. STATOR CURRENT

III - v_L - LINE VOLTAGE

IV - TIME SCALE, 60 cps

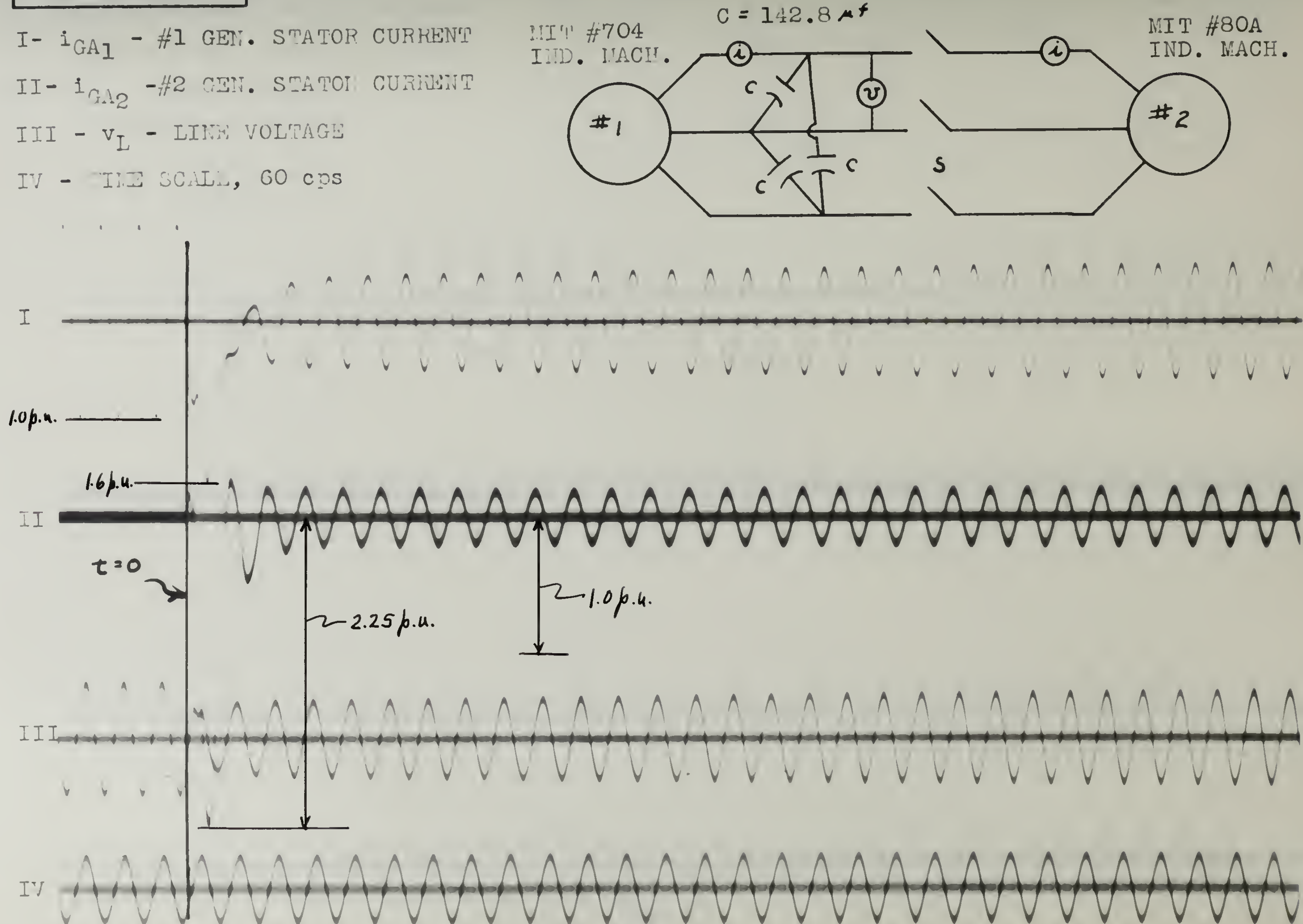


FIG. XIV

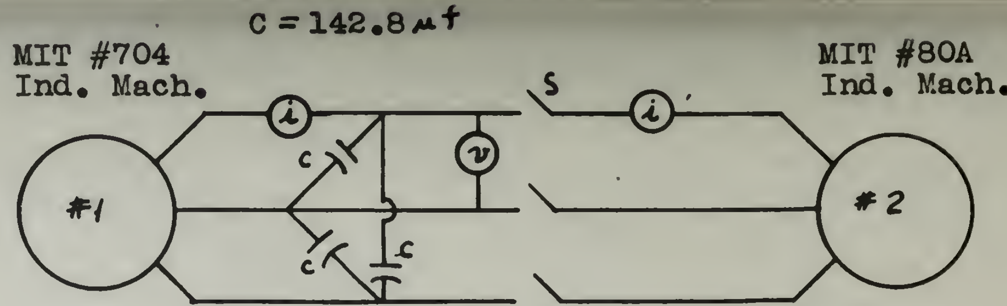
PARALLELING

I- i_{GA_1} - #1 gen. stator current

II- i_{GA_2}- #2 gen. stator current

III- v_L - line voltage

IV - time scale, 60 cps



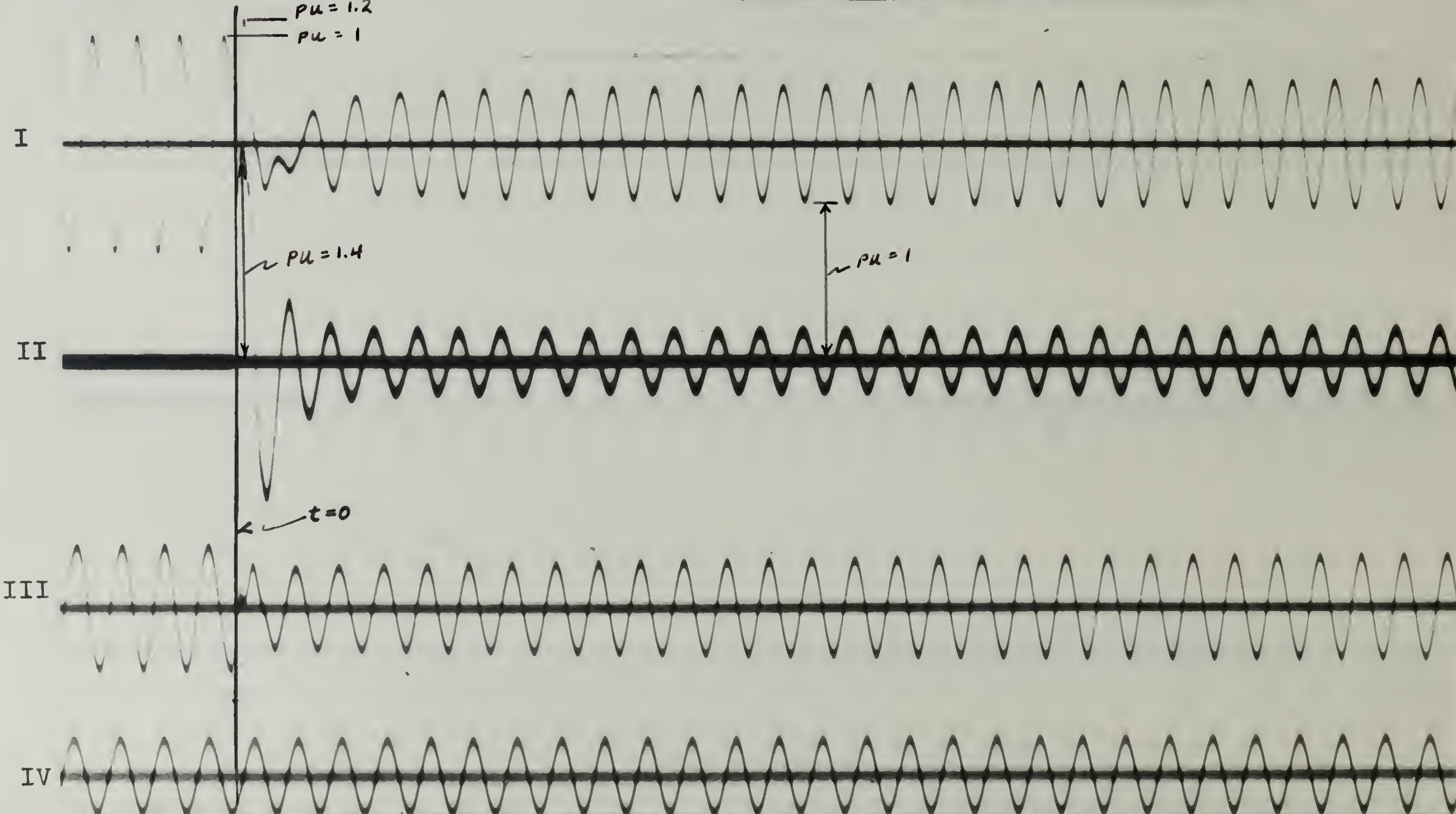


Fig. XV

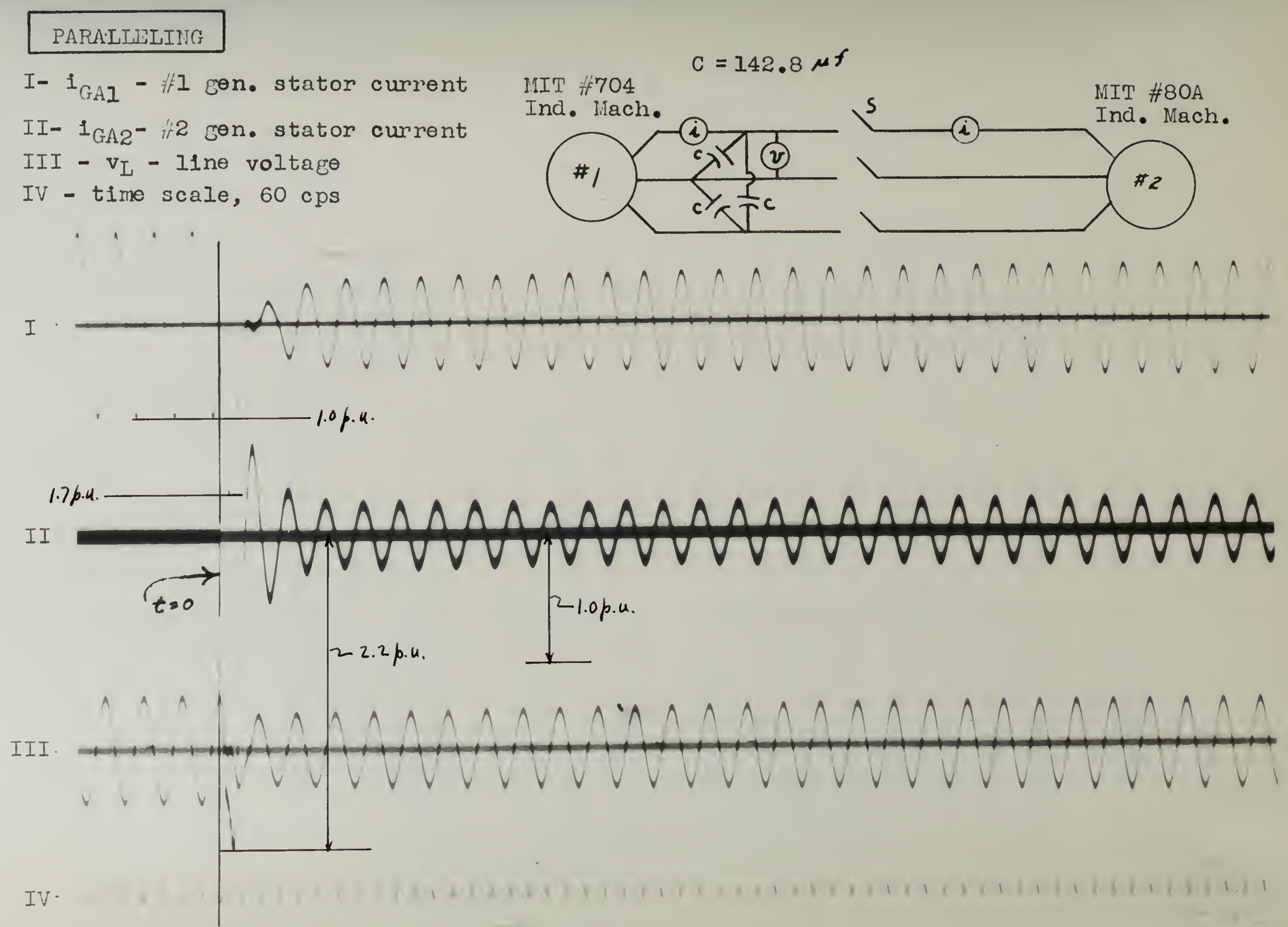

PARALLELING
I- i_{GA1} - #1 gen. stator current
II- i_{GA2}- #2 gen. stator current
III - v_L - line voltage
IV - time scale, 60 cps
C = 142.8 μf
MIT #704
Ind. Mach.
MIT #80A
Ind. Mach.
#1
#2
S
i
v
c
1.0 p.u.
1.7 p.u.
t=0
2.2 p.u.
1.0 p.u.
I
II
III
IV

Fig. XVI

V. CONCLUSIONS

The study made of the induction generator revealed the following:

(1) The induction generator with shunt capacitor-excitation can act as an independent generator; no load voltage build up, initiated by residual magnetism, is reinforced by the action of the excitation capacitance and continues to build up the voltage until saturation causes the machine's magnetizing reactance to equal the capacitative reactance of the excitation capacitors.

(2) If the induction generator fails to build up due to loss of residual magnetism, flashing the stator windings will reestablish the magnetism in the rotor.

(3) An induction generator can deliver power comparable to the power it is capable of absorbing when operating as an induction motor.

(4) Induction generators are well adapted to parallel operation.

(5) Generator transients occuring during normal or abnormal operation are of no consequence.

(6) Except for the possibility of over exciting the capacitor-excited induction generator either by

too much shunt capacitance or by too much leading power factor load, the induction generator is in itself quite foolproof.

Although it is not likely to supplant the synchronous generator for power and lighting loads at the conventional frequency of 60 cps, the induction generator may well find use in supplying power for the following applications:

(1) Laboratories or other activities desiring a voltage of pure sinusoidal waveform.

(2) Unattended power boosters in remote sections of power lines.

(3) Power plants generating at frequencies substantially above 60 cps.

VI. RECOMMENDATIONS

An outstanding advantage of the induction generator over the synchronous generator lies in the ability of the former to operate at much higher rotating speeds. This advantage is a direct consequence of squirrel cage rotor construction. Therefore, it is recommended that further investigation of the machine be made at higher rotating speeds and the corresponding higher frequencies.

The practicability of automatic voltage regulation using static devices, possibly saturable core reactors, should be investigated.

Transient response of the generator with compound capacitor-excitation is a field for further study.

Also a study of available magnetic materials might be made to determine which material has characteristics to give the best voltage regulation with a minimum of exciting losses.

VII. A P P E N D I X

DETAILS OF PROCEDURE

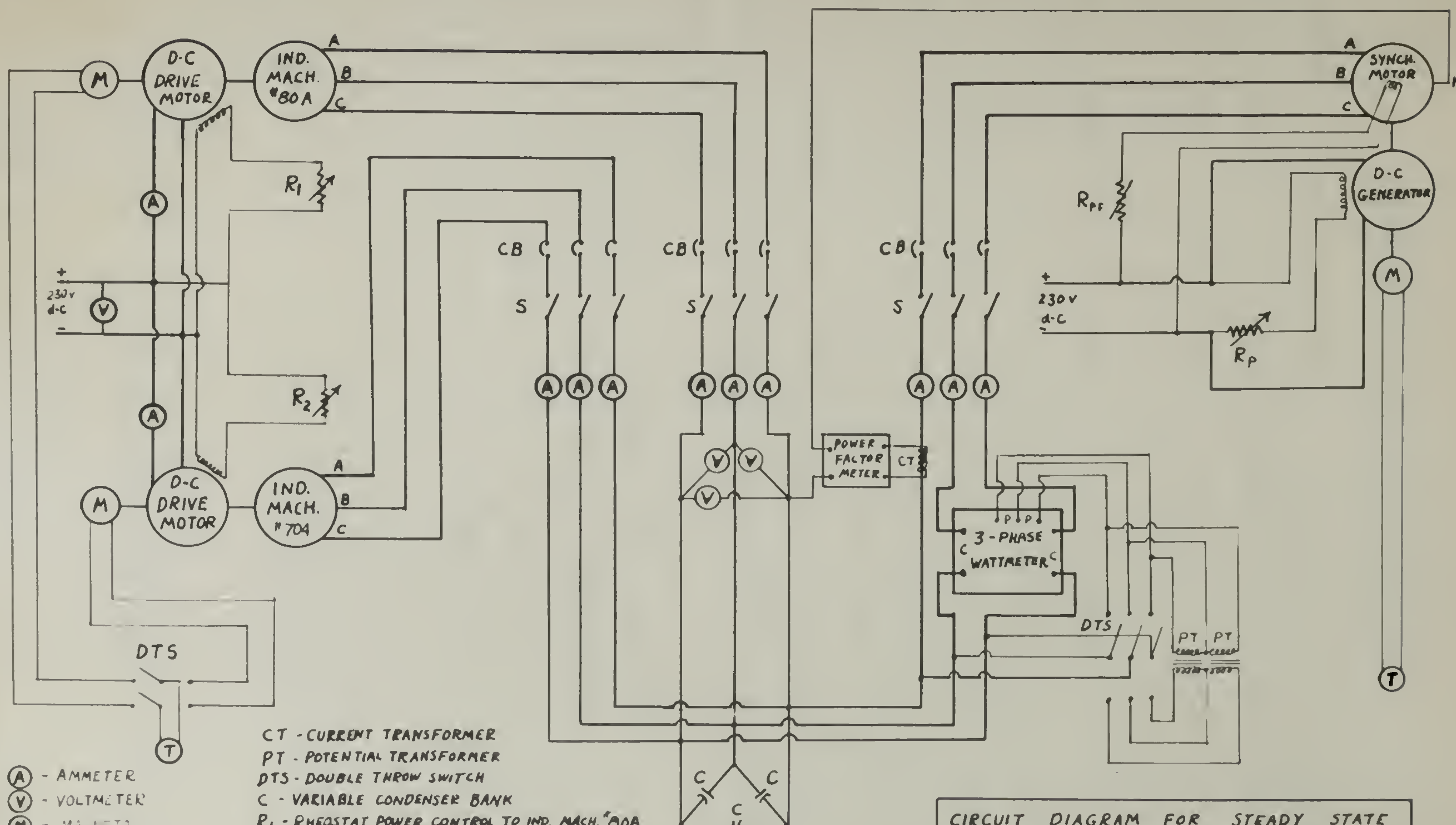
To obtain the experimental data for steady state and parallel operation characteristics, the circuit shown in Fig. A-I was used. For the sake of clarity, much of the extraneous wiring ----- such as the cathode ray oscilloscope connections and the synchronizing lamps between the synchronous motor (load) and generator terminals ---- have been omitted from this figure.

The rheostats R_1 and R_2 permitted the manual adjusting of generator frequency for single generator operation. For parallel operation these rheostats were further used to shift the load between generators.

To determine no load losses and also to determine the division of load in parallel operation, d. c. voltmeters and ammeters were used in the power leads to the drive motors.

The condensers (indicated by C in Fig. A-I) used for excitation purposes permitted a wide range and fine variation of the excitation capacitance. The following capacitors were available in each leg:

1 at 58.8 microfarads
1 at 29.4 "
7 at 28.8 "
1 at 14.7 "
1 at 8.0 "
1 at 7.4 "
1 at 4.0 "
1 at 3.7 "
1 at 2.0 "
1 at 1.0 "
1 at 0.5 "
1 at 0.4 "
1 at 0.2 "
1 at 0.1 "



Ⓐ - AMMETER
Ⓥ - VOLTMETER
Ⓜ - MAGNETO
Ⓣ - TACHOMETER
S - SWITCH
CB - CIRCUIT BREAKER

CT - CURRENT TRANSFORMER
PT - POTENTIAL TRANSFORMER
DTS - DOUBLE THROW SWITCH
C - VARIABLE CONDENSER BANK
R_1 - RHEOSTAT, POWER CONTROL TO IND. MACH. #80A
R_2 - RHEOSTAT, POWER CONTROL TO IND. MACH. #704
R_{pf} - RHEOSTAT, LOAD POWER FACTOR CONTROL
R_p - RHEOSTAT, LOAD POWER CONTROL

CIRCUIT DIAGRAM FOR STEADY STATE AND PARALLEL OPERATION TESTS

FIGURE A-I

In addition when compound excitation was investigated, a series capacitor of 188 microfarads per leg was used.

The load for steady state and parallel operation was a 6.7 HP synchronous machine which was used also as a synchronous condenser. The rheostat, R_{PF}, controlled the power factor of the load. This scheme was used because it overcomes the difficulty of attempting fine control of power factor using resistors, coils, and condensers. Another reason for choosing a synchronous motor load was to facilitate the determination of generator frequency. A tachometer attached to the synchronous motor shaft then indicated the line frequency.

The synchronous motor drove a d-c generator whose load was controlled by the rheostat, R_P, which determined the field current of the d-c machine. Also the d-c machine was needed to bring the synchronous machine up to speed before putting the latter on the line.

As can be seen in Fig. A-I, the circuit was adequately instrumented so that the following quantities were readily available:

Line voltage, each phase.
Generator stator current, each phase, each leg.
Line current to load, each phase.
Power to load.
Power factor of load.
Power to each prime mover.
Speed of each prime mover.
Frequency of line current.

DETAILS OF PROCEDURE (cont.)

A cathode ray oscilloscope connected across the capacitor terminals provided for constant inspection of the voltage waveform.

To facilitate the experimental work, and since the various machines used were scattered throughout the laboratory, all control and instrument leads were led back to the operating bench where all instruments and rheostats were located.

Much time was spent in attempting to find machines which generated balanced voltages, and machines which drew balanced line currents. Many combinations of generators and motors were tried before an acceptable degree of unbalance was attained. Within 5% was finally accepted. To maintain balance under different values of excitation, it was necessary to calibrate the condenser banks used.

For the transient studies a Westinghouse Type PA portable oscillograph was used. The instrument has four recording elements. For all oscillograms, except the transient response of the frequency regulator, standard elements, sensitivity 0.15 amps per inch were used. For recording the frequency in the above mentioned case, a sensitive element, 0.025 inches per amp, was used. A switch on the oscillograph synchronized the opening of the camera shutter with the closing of the coil controlled "guillotine" switch which initiated the transient.

DETAILS OF PROCEDURE (cont.)

The four elements were sufficient to obtain the pertinent data for each transient except the single phase short circuit when it was desired to record seven variables. An attempt was made to run the transient on two separate oscillograms. Of course, the difficulty of initiating the transient at exactly the same phase time was encountered. The two oscillograms shown in Fig. XII represent the closest agreement obtained in many attempts.

DATA

Nameplate Data Of Machines Used As Generators

I. MIT INDUCTION MACHINE NO. 704 (SQUIRREL CAGE)

Westinghouse Type CS Induction Motor

Frame 485C	Serial No. 4884645				Style 890120		
7.5 HP	220 volts		60 cps		3 phase		
Poles	4	-	6	-	8	-	12
Amps per terminal	19.7	-	19.3	-	25.3	-	33.8
Full load RPM	1710	-	1130	-	860	-	570

Temperature rise 50° C. in 1 hour at 100% load.

II. MIT INDUCTION MACHINE NO. 80A (SQUIRREL CAGE)

General Electric Co. Induction Motor Type KT 180 Form C

Serial No. 893560	6 poles	
5 HP	60 cps	3 phase
220 volts	14.2 amps	No load speed 1200 RPM

DATA

No Load Losses And Machine Efficiencies

I. MIT INDUCTION MACHINE NO. 704.

At no load, $V_L = 297$ volts:

$n = 900$ RPM.

$V_{DC} = 230$ volts.

$I_{DC} = 10.8$ amps. $P_{DC} = 2.49$ KW.

At no load, $V_L = 0$ volts (not excited):

$n \doteq 900$ RPM.

$V_{DC} = 231$ volts.

$I_{DC} = 1.8$ amps. $P_{DC} = \underline{0.415 \text{ KW}}$.

No Load Excitation Loss (for $V_L = 297$ volts) $= \underline{2.07 \text{ KW}}$.

At near rated load, $V_L = 246$ volts:

$n = 910$ RPM.

$P_{AC} = 4.8$ KW, Power Factor $= 1.0$.

$V_{DC} = 230$ volts.

$I_{DC} = 30.8$ amps. $P_{DC} = 7.1$ KW.

No Load Losses And Machine Efficiencies (cont.)

II. MIT INDUCTION MACHINE NO. 80A.

At no load, V_L = 296 volts:

n = 1200 RPM.

V_{DC} = 117 volts.

I_{DC} = 6.5 amps. P_{DC} = 0.76 KW.

At no load, V_L = 0 volts (not excited):

n = 1200 RPM.

V_{DC} = 118 volts.

I_{DC} = 2.0 amps. P_{DC} = 0.24 KW.

No Load Excitation Loss (for V_L = 296 volts) = 0.52 KW.

At near rated load, V_L = 246 volts:

n = 1230 RPM.

P_{AC} = 2.1 KW, Power Factor = 1.0.

V_{DC} = 112.5 volts.

I_{DC} = 32.5 amps. P_{DC} = 3.67 KW.

DATA

A. Steady State Characteristics

Run I. LOAD CHARACTERISTICS. Machine No. 80A, shunt excited. Frequency = 60 cps. C = 64 microfarads.

V_L volts	I_L amps	I_G amps	P_L KW	Power Factor	Lag/Lead
320	0	13.0	0	-	-
320	2.4	14.4	1.20	1.0	-
320	2.0	14.0	1.08	1.0	-
315	3.5	14.1	2.00	1.0	-
305	5.6	15.2	3.00	1.0	-
310	2.5	12.5	1.14	0.8	Lag
296	3.5	11.3	1.64	0.8	Lag
273	4.6	10.0	1.90	0.8	Lag
301	3.0	11.6	1.36	0.8	Lag
330	2.4	15.0	1.10	0.8	Lead
332	2.7	15.6	1.24	0.8	Lead
338	3.5	16.7	1.60	0.8	Lead
342	4.2	17.6	1.92	0.8	Lead
344	4.4	17.8	2.08	0.8	Lead

DATA

A. Steady State Characteristics (cont.)

Run IIA. LOAD CHARACTERISTICS. Machine No. 704, shunt excited. Frequency = 60 cps. C = 142.8 microfarads.

V_L volts	I_L amps	I_G amps	P_L KW	Power Factor	Lag/Lead
274	0.0	26.8	0.00	-	-
268	2.5	26.8	1.26	1.0	-
266	4.1	26.6	1.96	1.0	-
252	13.1	29.2	5.50	1.0	-
248	13.4	29.3	5.80	1.0	-
234	5.4	19.7	1.76	0.8	Lag
230	6.6	19.3	2.24	0.8	Lag
203	7.6	16.5	2.74	0.82	Lag
258	2.6	23.7	1.04	0.82	Lag
276	3.0	28.9	1.23	0.81	Lead
282	5.3	31.3	2.00	0.77	Lead
279	12.9	35.6	5.50	0.85	Lead
279	5.1	30.8	1.88	0.76	Lead

Run IIB. Frequency = 120 cps. C = 28.0 microfarads.

V_L volts	I_L amps	I_G amps	P_L KW	Power Factor
455	0	17.2	0	-
414	5.0	16.3	3.68	1.0
311	7.5	13.8	4.28	1.0

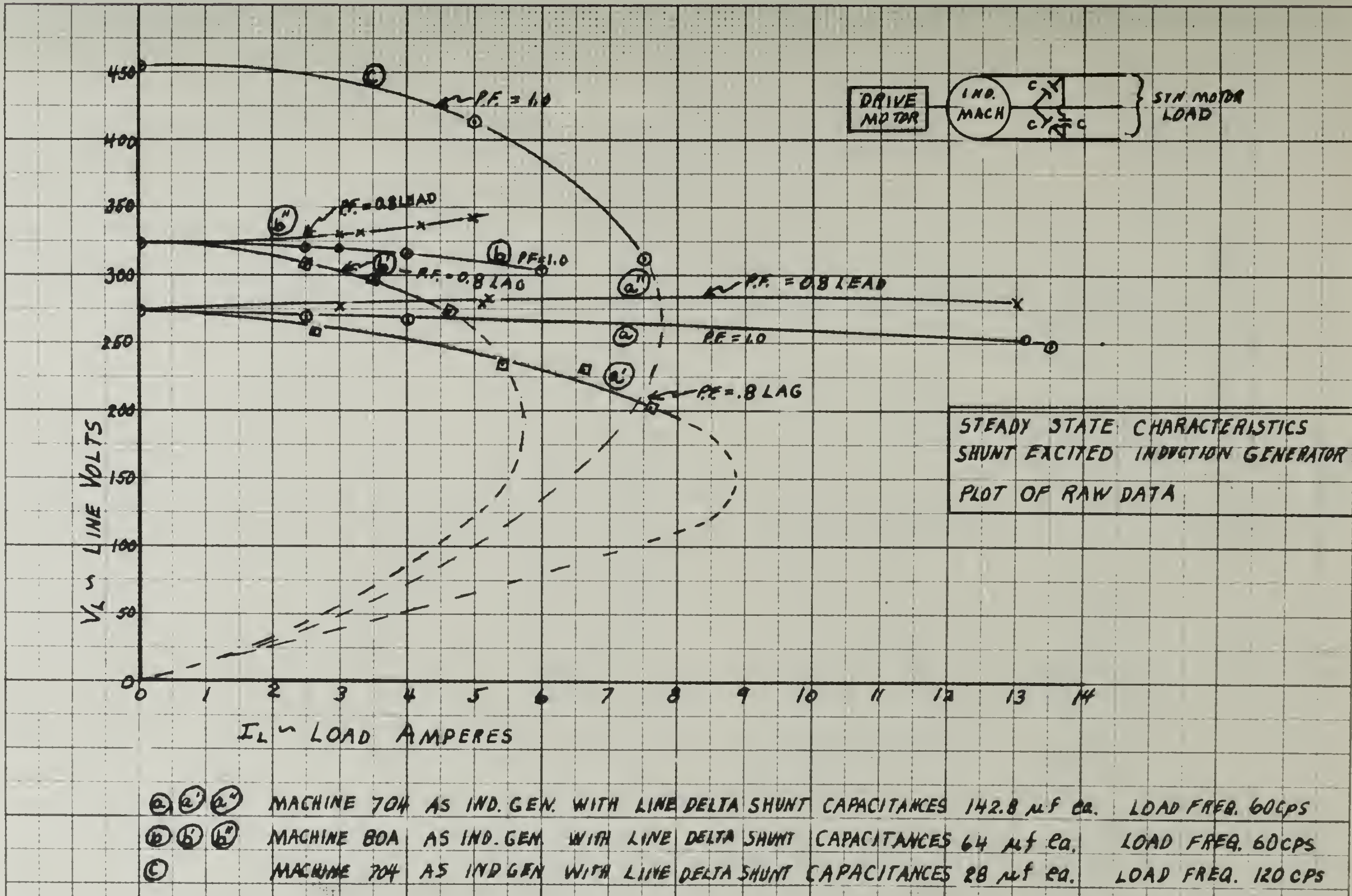


FIG A-II

HOSSONG & ESTES 3-3-51
O.F.G.

DATA

A. Steady State Characteristics (cont.)

Run III. LOAD CHARACTERISTICS. Machine No. 80A, compound excitation. Frequency = 60 cps. Shunt capacitance, C = 66 microfarads; series capacitance, C_L = 188 microfarads. Power factor of load = 1.0.

V_G volts	V_L volts	I_G amps	I_L amps	P_L KW
305	307	11.6	0.0	0.00
297	292	12.5	3.4	1.94
308	270	16.0	6.5	3.20

Run IV. FREQUENCY REGULATOR CHARACTERISTICS. Power factor of load is unity.

P_L KW	Synchronous Motor Speed RPM	Frequency cps
0	1800	60.0
2.0	1795	59.8
2.6	1794	59.8
3.1	1793	59.8
3.8	1792	59.7
4.6	1791	59.7
5.1	1789	59.6
5.4	1789	59.6

DATA

B. Transients

Note: Machine No. 704 generating at 60 cps was used for all transient studies.

Run I. No Load Voltage Build Up. Refers to Fig. VI.

$C = 142.8$ microfarads.

Final $V_L = 278$ volts.

Final $I_G = 27.2$ amps.

Run II. Starting An Induction Motor.

(a) Machine No. 709, 3/4 HP, wound rotor motor. $C = 142.8$ microfarads. Refers to Fig. VII.

Before start:

$V_L = 268$ volts.

$I_G = 24.5$ amps.

After start (steady state):

$V_L = 253$ volts.

$I_G = 21.5$ amps.

$I_L = 2.5$ amps.

(b) Machine No. 713, 1 HP, squirrel cage motor. $C = 200$ microfarads. Refers to Fig. VIII.

Before start:

$V_L = 330$ volts.

$I_G = 43.0$ amps.

After start (steady state):

$V_L = 320$ volts.

$I_G = 41.0$ amps.

$I_L = 2.0$ amps.

B. Transients (cont.)

Run III. 3 Phase Short Circuit.

(a) From light, balanced load. C = 142.8 microfarads. Refers to Fig. IX.

Before short:

V_L = 242 volts.

I_G = 21.7 amps.

I_L = 5.8 amps.

(b) From rated, balanced load. C = 142.8 microfarads. Refers to Fig. X.

Before short:

V_L = 205 volts.

I_G = 24.2 amps.

I_L = 14.6 amps.

(c) From unbalanced load, C = 200 microfarads. Refers to Fig. XI.

Before short:

$V_{L_{AB}} = V_{L_{BC}}$ = 294 volts.

$V_{L_{CA}}$ = 290 volts.

$I_{L_A} = I_{L_C}$ = 13.4 amps.

I_{L_B} = 10.0 amps.

$I_{G_A} = I_{G_C}$ = 34.3 amps.

DATA

B. Transients (cont.)

Run IV. Single Phase Short Circuit. C = 142.8 microfarads. Refers to Fig. XII.

Before short:

V_L = 205 volts.

I_G = 24.2 amps.

I_L = 14.6 amps.

Run V. Paralleling. Refers to Figs. XIV, XV, and XVI.

Before paralleling:

Machine No. 704, designated below by subscript "1", on the line. Machine No. 80A running unexcited at 1215 RPM.

I_{G_1} = 22.6 amps.

V_L = 275 volts.

C = 142.8 microfarads.

After paralleling:

I_{G_1} = 15.8 amps.

I_{G_2} = 5.5 amps.

V_L = 225 volts.

C = 142.8 amps.

DATA

C. Parallel Operation

Run I. Load Characteristics of Machines No. 704 and No. 80A Paralleled. Excited by a common condenser bank. Frequency = 60 cps.

V_L volts	I_L amps	P_L KW	Power Factor	I_G amps	V_{DC} volts	I_{DC} amps	P_{DC} KW	I_G amps	V_{DC} volts	I_{DC} amps	P_{DC} KW	C μf
263	0.0	0.00	1.0	23.4	232	6.5	1.51	7.6	115	4.5	0.52	173
257	1.4	0.82	1.0	23.3	232	9.5	2.20	7.4	114	5.4	0.62	173
255	3.4	1.64	1.0	23.0	232	12.3	2.85	7.3	114	7.5	0.85	173
235	11.8	5.0	1.0	22.7	231	24.6	5.69	7.4	113	16.2	1.83	173
225	15.1	6.0	1.0	22.6	231	25.5	5.90	8.4	113	25.7	2.91	173
247	10.5	4.7	1.0	23.8	232	21.3	4.95	8.3	113	20.4	2.31	190
246	15.7	7.0	1.0	26.2	230	30.8	7.10	9.6	113	32.5	3.67	218

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